# DESIGN, DEVELOPMENT AND PERFORMANCE OF A FLAT PLATE SOLAR AIR HEATER WITH HONEYCOMB TRANSPARENT INSULATION

*by*

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**AUGUST, 1993**

# CERTIFICATE

Certified that the thesis entitled " DESIGN, DEVELOPMENT AND PERFORMANCE OF A FLAT PLATE SOLAR AIR HEATER WITH HONEYCOMB TRANSPARENT INSULATION " by Mr. Brijesh Dixit has been carried out under my supervision and that this work has not been submitted elsewhere for the award of a degree.

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# ABSTRACT

The thesis is an experimental investigation carried out to study the effect of a Polymethylmethacrylate (PMMA) or Perspex-honeycomb on the frontal heat losses of a flat plate solar air heater. A flat plate air heater, having a square celled perspex honeycomb strcuture between the absorber plate and the glass cover, was fabricated and tested over a wide range of air flow rates. The honeycomb cells were sized small enough to provide natural convection suppression but had little effect on radiation suppression.

In order to carry out a comparative evaluation of the influence of the honeycomb on the frontal heat losses, the collector was also tested without the honeycomb, keeping absorber plate - glass cover air gap equal to 1.5 and 5.5 cm.

It was found that the honeycomb collector gives maximum air temperatures and collector efficiencies for all flow rates. The plain collector with absorber plate glass cover air gap equal to 1.5 cm, was the least efficient and gave the lowest air temperatures. Increasing the air gap to 5.5 cm resulted in an improvement in the efficiency and an increase in the air temperature, over the previous case.

# ACKNOWLEDGEMENTS

I wish to express my deep sense of gratitude and sincere regards to Dr. H.C. Agrawal for his invaluable guidance and constant encouragement in the successful completion of this work.

I express my gratitude to Mr. U.S. Dixit who constantly helped me in writing this thesis. I also wish to thank my friends - Amit, Balwinder, Vinoy, Amod, Manoj, Sameer, Sunil and others, who apart from making my stay at Kanpur very pleasant and memorable, also helped me from time to time.

I also wish to express my appreciation to Mr. S.N. Sharma, for his sincere efforts and assistance, provided in the fabrication work and to Mr. R.C. Vishwakarma for typing of the thesis.

BRIJESH DIXIT

# CONTENTS

# NOMENCLATURE

| | |
|---|---|
| $d_h$ | Hydraulic diameter, mm,cm |
| $\eta$ | Collector efficiency, % |
| $\eta_o$ | Optical efficiency, % |
| U | Overall heat loss coefficient, $W/m^2\ ^oC$ |
| $\rho$ | Fluid density , $kg/m^3$ |
| Q | Volume flow rate, L/s |
| $C_p$ | Specific heat of air at constant pressure, $kJ/kg\ ^oC$ , $J/kg^o$ |
| dt | Time interval, hours |
| $T_{fi}$ | Fluid inlet temperature, $^oC$ |
| $T_{fe}$ | Fluid outlet temperature, $^oC$ |
| $H_t$ | Incident solar radiation on a horizontal surface $kW\text{-}hr/m^2$ |
| R | Correction factor to account for the tilt of the collector from the horizontal |
| $A_c$ | Cover glass area, $m^2$ |
| Gr | Grashof's number |
| Ra | Rayleigh's number |
| q | Heat flux per unit time, W |
| L | Characteristic dimension, the width of the channel, m |
| y | Volumetric expansion of the fluid, $m^3/m^3\ ^oC$ |
| $\mu$ | Dynamic viscosity, kg/ms |
| k | Thermal conductivity of air, $W/m\ ^oC$ |
| x | Length of the channel, m |

# LIST OF FIGURES

# LIST OF PHOTOGRAPHS

# CHAPTER 1

# INTRODUCTION

## 1.1 ENERGY CRISIS

The fascinating story of human development from the stone age to the space age, has been made possible by the exploration and harnessing of different sources of energy for the productive endeavours of man. Perhaps, after food, energy is the most important input for the material advancement of human civilization. This is especially true in today's world where the amount of energy consumed is being increasingly used as a direct indicator of the level of social, economic and infrastructural development of a country.

Against this backdrop, the dwindling supplies of commercial fuel, such as coal, oil and natural gas etc., are bound to generate a considerable amount of skepticism as to the future. In fact, such is the gravity of the situation, that if something is not done soon enough, it may assume crisis proportions.

This brings us to the role of renewable energy sources, such as SOLAR, WIND, TIDAL, OCEAN etc., which offer immense possibilities for solving our energy problems for all times to come. Of all these sources, solar energy is particularly useful for a variety of reasons mentioned below.

## 1.2 SOLAR ENERGY

The earth receives an astonishing 75,000 trillion kWh of energy from the sun each day, of which only 0.1 percent is sufficient to solve all our energy problems.

The special promise of solar energy lies in its diffuse nature and world wide availability. Solar energy has a great future in a tropical country like India, where many places receive a peak solar flux of the order of 0.1 $kW/m^2$ [1].

The main problem of utilizing solar energy lies in developing commercially viable technologies for harnessing it. A great deal of research and development is required before solar energy can compete favourably with conventional energy sources, and herein lies the challenge which scientists and engineers alike will be facing in the 90's and beyond.

## 1.3 APPLICATION OF SOLAR ENERGY

To conclude this chapter, a brief mention of some of the viable applications of solar energy would not be out of order:

### (A) SOLAR WATER HEATING

Many flat plate collectors have been designed for heating water. They consist of a box with glass or plastic covers, covering a metallic absorber element carrying water. Water is heated by the solar energy absorbed by the blackened absorber plate.

## (B) SWIMMING POOL HEATING

It is one of the simplest and the least expensive heating devices. It usually consists of a galvanized iron sheet wrapped in plastic. The sheet is painted with a good absorbing paint. Water from the pool can be fed to these absorbers by the filter pump and then into the pool.

## (C) SPACE HEATING

The objective here is to heat a house or a building. This is normally achieved by using a solar air heater (active solar heating) or by designing the house itself so as to trap the incident solar energy (passive solar heating).

## (D) SOLAR COOKING AND BAKING

The simplest type of Solar Cooker is a box with a glass cover facing the sun. Mirrors are provided to give some degree of concentration, which would bring the food to be cooked, up to the cooking temperature quickly.

## (E) SOLAR DISTILLATION

One of the major problems in many parts of the world is the non availability of fresh water. Solar stills can convert saline or brackish water into potable water easily, by the process of evaporation and condensation.

## (F) CONVERSION TO ELECTRICITY

If electricity is desired as the end product, it can be produced by converting solar energy into mechanical power and then driving a conventional generator using this mechanical power. Alternatively, solar energy can be converted directly into electricity by one of the solid state devices commonly known as the solar cells.

Some other uses of solar energy worth mentioning are:

Solar refrigeration and air conditioning, solar furnaces, solar pumps, solar cars for transportation etc.

# CHAPTER -2

# SOLAR COLLECTORS AND TRANSPARENT INSULATION

## 2.1 SOLAR COLLECTORS

A solar collector is a device for intercepting incident solar radiation, converting it to heat in a fluid and delivering the heated fluid for use.

Solar collectors are essential components of most solar energy devices. Indeed, quite a substantial fraction of the cost of solar devices is covered by the cost of solar collectors. Therefore, it is of utmost importance that research and development be vigorously pursued, with the view towards increasing the efficiency and reducing the cost of solar collectors.

## 2.2 TYPE OF SOLAR COLLECTORS

Solar collectors may be divided into concentrating and non-concentrating collectors

Concentrating collectors are those in which the area of surface absorbing the solar radiation is much less as compared to the area which is exposed to the sun's rays. This results in increased collector temperatures of the order of 140 $^{o}C$. Concentrating collectors absorb only the direct part of the incident radiation. They need continuous tracking mechanisms and a more expensive mounting (pivoting) structure than non-concentrating collectors.

Figure 2.1 shows the rate of concentration of various kinds of solar collectors. The picture at the top shows a flat-plate collector, which does not concentrate the solar radiation at all. The next picture shows a cylindrical trough collector in which the focal line can concentrate 2-40 times. By means of heliostats placed around a solar tower (the power-tower concept) it is possible to concentrate the solar rays 100-2,000 times in a boiler placed at the top of the tower. Finally, by means of a parabolic mirror it is possible to obtain concentrations between 100-10,000 times.

Non-concentrating collectors are those in which the area of the surface on which solar radiation is absorbed is approximately equal to the area exposed to the sun's rays. They absorb the direct as well as the diffuse parts of the incident radiation. The solar absorbing surfaces in most non-concentrating collectors are substantially flat or planar. Such collectors are referred to as flat plate collectors.

Flat plate collectors have evoked a great deal of interest in recent years, primarily because of their simple design, ease of fabrication and wide range of potential applications.

## 2.3 MAIN COMPONENTS OF A SOLAR COLLECTOR

Solar collectors are quite simple in concept and consist of the following main components:

1. A solar absorber which is designed to absorb the incident solar radiation and transfer it to the heat absorbing fluid.

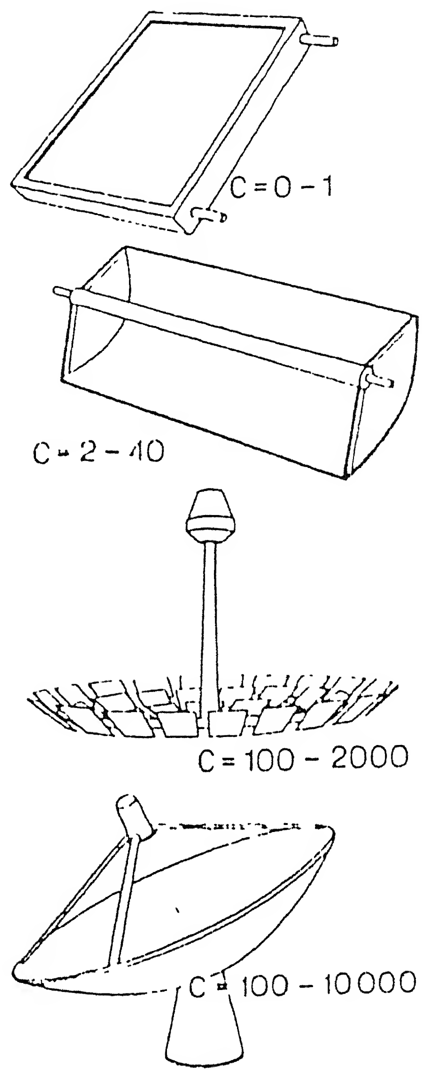



FIG. 2.1: RATES OF CONCENTRATION OF VARIOUS KINDS OF SOLAR COLLECTORS.

It usually consists of a metal plate, or an assembly of metal sheets or plates forming a nearly continuous surface, coated with a solar absorbing substance such as black paint, black porcelain enamel, or metallic black oxide.

2. One or more flow passages for the heat transfer fluid.

3. Transparent covers, usually of tempered window glass, which reduce thermal losses to the atmosphere by providing one or two stagnant air layers for suppression of convention losses. The opacity of glass to long wave radiation (above 5 $\mu m$) emitted by the absorber surface reduces radiation losses as well.

4. A layer of insulation below the absorber- flow channel assembly which inhibits the downward heat loss.

5. A shallow box on casing which provides a rigid, protective structure for the entire collector assembly.

6. A concentrator which may be used to increase the solar energy incident on the absorber,and thereby achieve higher collection temperatures.

Fig. 2.2 represents a simple flat plate collector showing the above components.

### 2.3.1 TYPICAL AIR COLLECTOR

Fig. 2.3 is a perspective sketch of a typical air-heating solar collector. The principal difference between air and liquid collectors is with respect to the size and arrangement of the

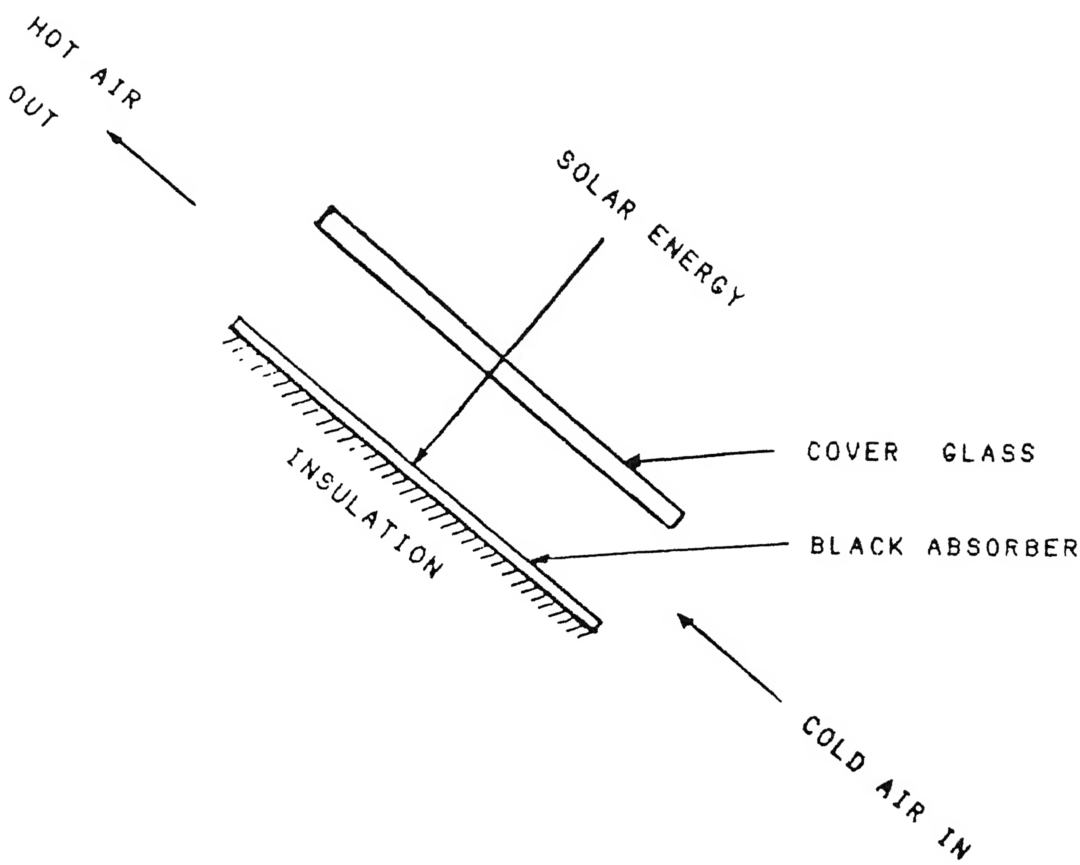



FIG. 2.2: A SIMPLE FLAT PLATE AIR HEATER.

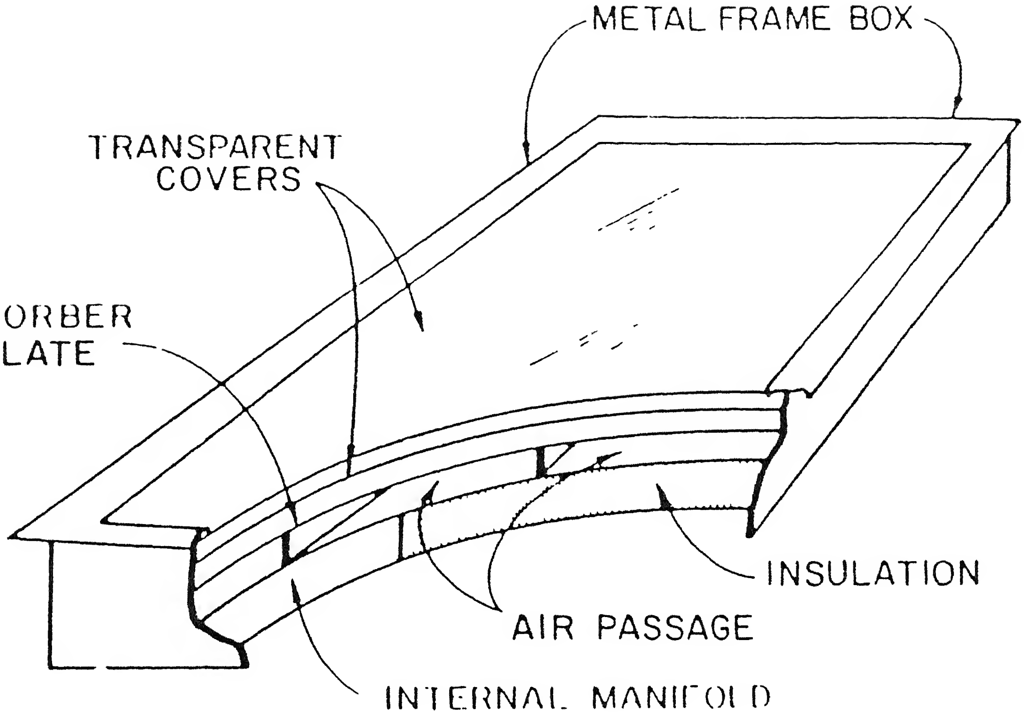



FIG. 2.3: A TYPICAL FLAT PLATE SOLAR AIR HEATER.

fluid conduits. The figure shows an air passage, about 1 to 1.5 cm high, beneath the absorber plate. For effective heat transfer, air flows below, and in contact with, the entire absorber surface. The design also has internal manifolds for air distribution to all collector panels in a close-fitting array.

## 2.4 CLASSIFICATION OF SOLAR COLLECTORS

Solar collectors can be classified on the basis of:

1. Collector orientation
2. Working Fluid
3. Type of covers, absorber and concentrator (if present).

### 2.4.1 COLLECTOR ORIENTATION

Solar collectors can be classified as fixed or tracking. Fixed collectors are those which do not move during the course of the day. In the northern hemisphere they face south and are tilted from the horizontal, at an angle equal to the latitude, to favour year round collection. A $15^0$ greater tilt favours winter collection, while a $15^0$ lesser tilt favours summer collection. Such fixed collectors have the advantage of simplicity, reliability, and low maintenance. On the other hand, fixed collectors are often irradiated by the sun at unfavourable angles. A mount which allows the collector to always, face the sun exposes the area to maximum irradiation. Whenever high concentration is required to achieve high temperatures, the collector (or some component of it) must track the sun accurately. These are called tracking collectors.

Semi-fixed collectors may also be used. For example, a booster may change the position once a day, or the angle may be adjusted seasonally. Even a simple flat plate collector may be tilted to a near vertical in the winter and a near horizontal in the summer to obtain more favourable angles of solar irradiation.

### 2.4.2 WORKING FLUID

Solar collectors can also be classified on the basis of the working fluid used, such as air heaters and water heaters. Hydrocarbons, halogenated hydrocarbons and anti-freeze mixtures are also used, particularly when power generation or refrigeration is the goal.

For good technical performance and heat transfer, the working fluid should have a high thermal conductivity, a low viscosity, and a high specific-heat-density product. On this basis, air would be the least desirable, water intermediate and liquid metals the most desirable. Yet, no liquid metal solar collectors are presently built. Other factors such as a low freezing point, non-corrosive nature, safety to life and property and low cost, overturn a simplistic ranking on the basis of only heat transfer performance.

When warm air is used for drying and space air conditioning, the non-corrosive nature of air permits the use of very inexpensive materials and the prospect of leaks developing inadvertently poses no threat to property. Also air cannot freeze or boil. However, it's low density and specific heat dictate high flow rates that may result in the consumption of significant fan power, larger ducts, and excessive noise.

Heat transfer coefficients of air are approximately two orders of magnitude lower than those of water. Thus, while the wall water surface area is of minor importance in the design of solar collectors without high concentration, it is of concern for air heaters, even when no concentrator is used. If the area available for heat exchange is not greater than the projected area of the absorber, that is, the area projected onto a plane surface perpendicular to the sun's rays, then the absorber temperature may have to be 10 to 50 $^{o}C$ higher than that of the air itself to transfer the solar energy to the working fluid. If the absorber is at a very high temperature, the heat transferred by it to the cover glass is also quite significant, and some energy is lost. A high ratio of heat exchange area to the projected absorber area is thus quite desirable and forms an important parameter for a rational design of an air heater.

### 2.4.3 COVER, ABSORBER AND CONCENTRATOR

#### 2.4.3.1 COVER

The cover, usually of tempered window glass is used to reduce the thermal losses to the atmosphere. Glass has the property of allowing the short wavelength (less than 5 $\mu m$) incident radiation to pass through while being opaque to the long wavelength (above 5 $\mu m$) radiation emitted by the absorber plate. Further, it can reduce the convective losses by providing one or more layers of stagnant air above the absorber plate.

When the glass cover is non existent, the collector is known as unglazed while the term single glazed or multi glazed is used if one or more glass covers are employed.

The convective and radiative losses can be further supressed by using a plastic honeycomb structure in the absorber glass cover air gap. Such a collector referred to as a honeycomb collector has been developed by Francia of Italy (Fig. 2.4). In this collector the multiple glazing, otherwise used to prevent the frontal heat losses is replaced by a honeycomb structure normal to the plate. The honeycomb structure can serve to produce relatively stagnant air conditions, limiting the convective losses. It can also limit the infrared radiation losses by being made of walls essentially black to the infrared. The honeycomb concept works best when the panel is pointed at the sun, so that sunlight is streaming into the honeycomb with no shadowing. With a glass honeycomb, or other material transparent to solar radiation and opaque to infrared, this is however, not strictly necessary since sunlight will go through the walls.

Cylindrical evacuated covers can also be used to eliminate the natural convection between the absorber and the cover (Fig. 2.5).

### 2.4.3.2 ABSORBER

The absorber can be selective or non-selective. A selective absorber is one with a specially treated surface which absorbs the radiation of short wavelength in the solar spectrum but reflects the infrared radiation of longer wavelength. A

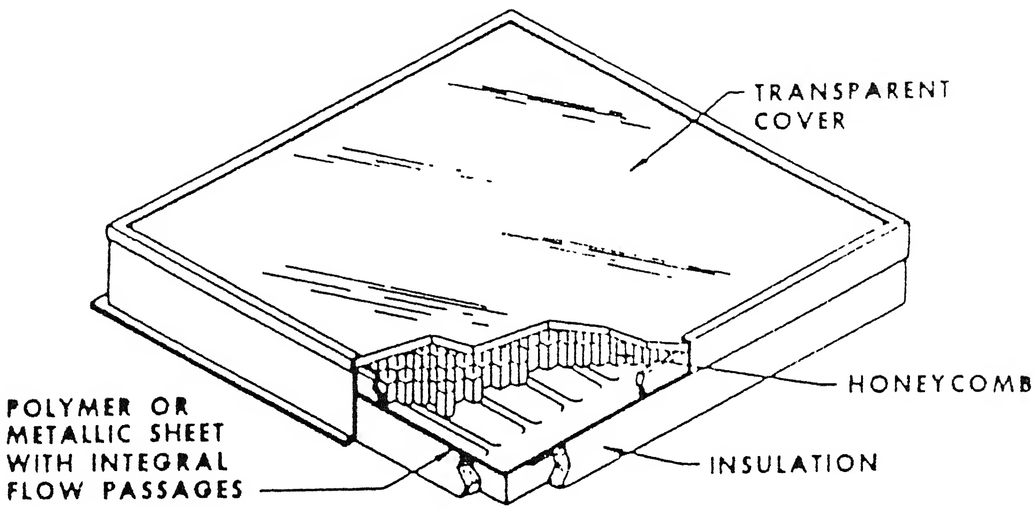



FIG. 2.4: A HONEYCOMB SOLAR COLLECTOR.

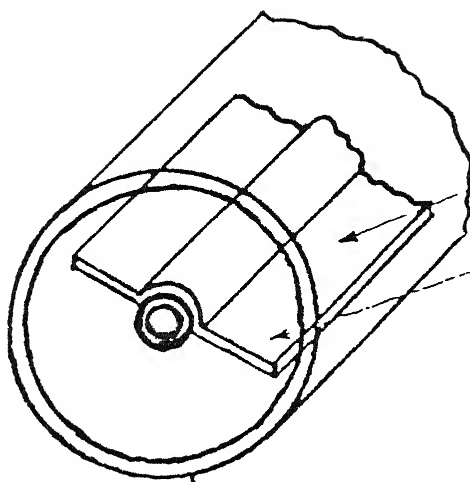



FIG. 2.5: AN EVACUATED GLASS COVER COLLECTOR.

non-selective absorber on the other hand absorbs all the incident radiation.

The absorber can also be in the form of a narrow bed of blackened fiberglass wool, through which air passes and gets heated up in the process (Fig. 2.6).

### 2.4.3.3 CONCENTRATOR

A variety of concentrators have been used for solar collectors. Common are the parabolic, like a searchlight mirror, and the cylindrical parabola, only slightly curved. A field of mirrors, each mirror tracking the sun and focusing the solar radiation upon an absorber mounted on a tower or a similar structure, has been used for solar furnaces and solar heat power generation purposes (Fig. 2.7).

## 2.5 TRANSPARENT INSULATION

Transparent insulation is a very crucial component in practically every type of thermal conversion of solar energy. It is fairly easy to provide opaque insulation against heat loss, but to combine good insulation with good optical transmission was considered for many years to be wishful thinking. In the past history of solar thermal conversion,the only possibility was conventional glazing with all its shortcomings. But in the form of evacuated insulation, glazing is still very much a contender.

Besides glazing, two types of materials structures have made strong progress in recent years, namely plastic honeycombs and aerogels. The practical importance of transparent insulation

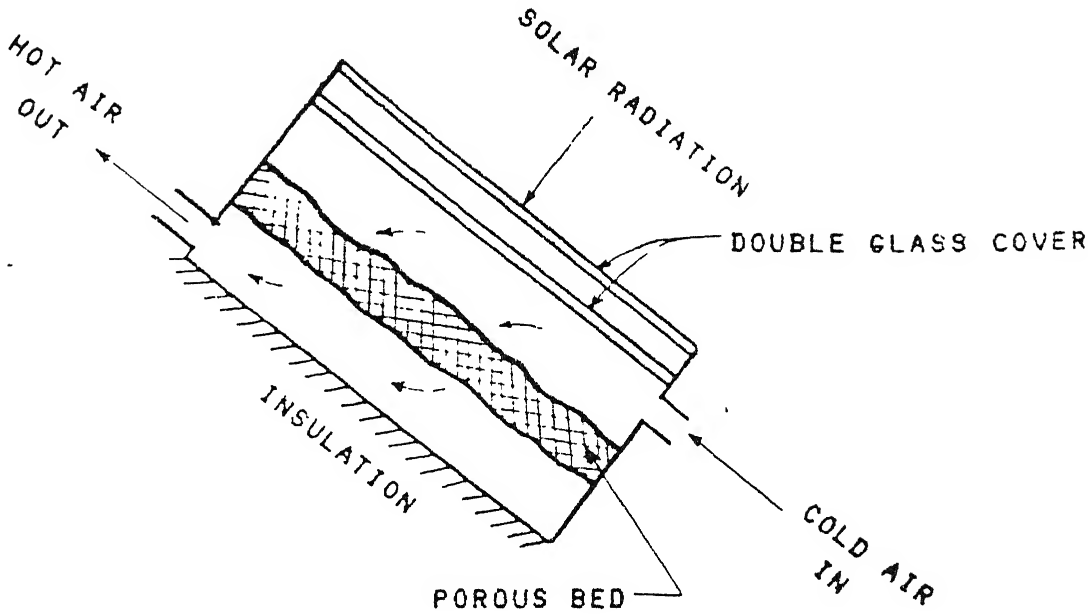



FIG. 2.6: A POROUS-ABSORBER AIR HEATER.

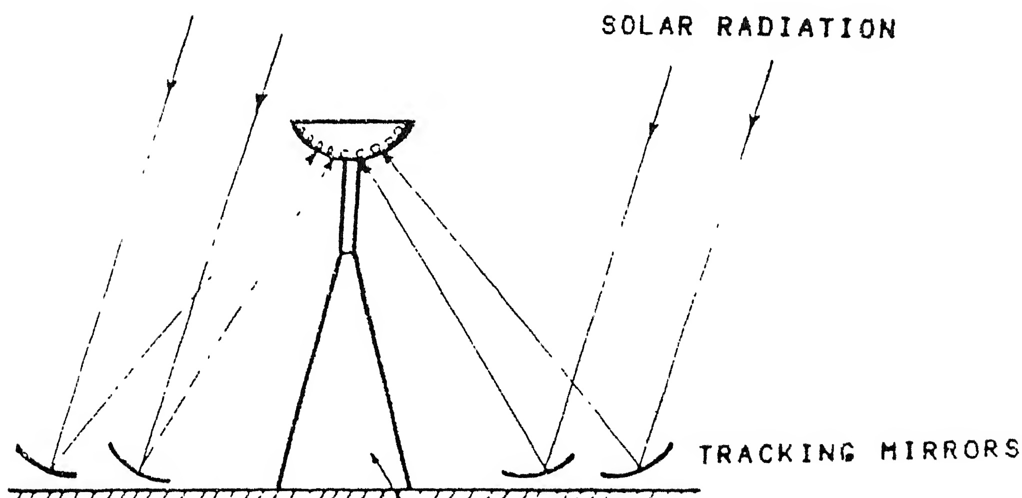



FIG. 2.7: A FIELD OF MIRRORS CONCENTRATOR.

materials resides in their applications. Applications are still in a very early stage, but already it can be said that they are extremely promising. Much better collectors can be designed with these materials. Good prospects are also related to applications in buildings and passive solar utilization. Considering the large amount of energy consumed for space heating worldwide,the prospects for energy savings are enormous.

The subsequent sections of this chapter are devoted to the application of plastic honeycomb structures in solar collectors to limit the frontal heat losses and improve the efficiency.

## 2.6 APPLICATION OF HONEYCOMBS TO SOLAR COLLECTORS

The use of honeycombs as cover materials for solar collectors aims at a reduction of frontal heat losses accompanied by only small solar transmission losses.

Typical state-of-the-art flat-plate collectors with a single glazing and a selective absorber have heat loss coefficients (U-values) of approximately 4 $W\ m^{-2}\ K^{-1}$ and optical efficiencies $\eta_o$ of about 80%. Due to these characteristic values, they are suitable for all applications,where the typical working temperatures are between 40 to 60 $^oC$, as is mainly the case in domestic hot water systems.

But there are many thermal processes with higher working temperatures in a range between 80 and 150 $^oC$. They include desalination systems, cooling processes with absorption or adsorption cycles and systems where saturated water vapour is needed (e.g., sterilizers). These processes as well as certain

solar cooker designs require collectors with lower heat loss coefficients than mentioned above, resulting in higher collector efficiencies.

The application of presently available Transparent Insulation Materials (TIMs) offers good possibilities to improve the performance of flat-plate collectors in the temperature range above 80 $^{o}C$. These materials have heat transfer coefficients of approximately 1 W $m^{-2}$ $K^{-1}$ and a diffuse-hemispherical solar transmittance of 70% [9].

FRANCIA [1961] developed a collector concept in which the multiple glazing, otherwise used to prevent the frontal heat losses, was replaced by a honeycomb structure normal to the absorber plate (Fig.2.4). The convective losses were suppressed by the relatively stagnant air conditions provided by the honeycomb cells, while the radiative losses were suppressed by the walls of the honeycomb which were essentially black to the infrared.

## 2.7 RADIATION AND CONVECTION SUPPRESSION USING HONEYCOMBS

Meinel and Meniel [2] discussed the mechanics of radiation and convection suppression using honeycombs. A brief description is given in the ensuing sections:

### 2.7.1 RADIATION SUPPRESSION

A honeycomb structure, as shown in Fig. 2.8 has certain properties useful in suppressing thermal infrared radiation from a hot surface, as originally shown by Hottel [1927]. Such

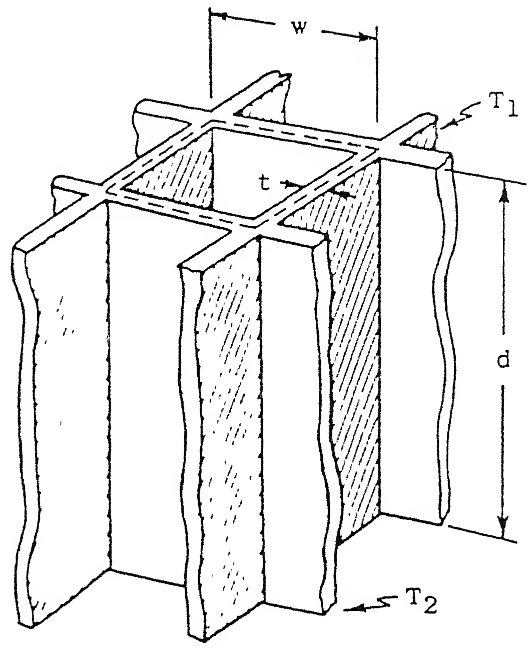



FIG. 2.8: SCHEMATIC DIAGRAM OF A HONEYCOMB MESH.

structures when properly constructed act very much like selective surfaces and have potential uses in solar energy collectors. If the walls of the honeycomb are "black" to thermal infrared, then the $2\pi$ solid angle of thermal radiation emitted from the absorber will largely be absorbed by the walls of the honeycomb. Only the solid angle of the upper opening of the honeycomb will permit radiation to escape directly to the sky. The radiation absorbed by the honeycomb will be remitted at a new temperature, that of the wall of the honeycomb. Secondary emission from the walls near the bottom of the honeycomb is also reabsorbed by the walls, with little escaping directly out of the aperture of the honeycomb. As a consequence of these multiple absorptions and emissions, the thermal radiation actually emerging from the honeycomb is effectively at a much lower temperature than that of the absorber.

Radiation-suppressing meshes for solar applications were first explored by Veinberg and Veinberg [1929]. Francia [1961] improved the method of construction for a series of solar power plant designs. The first designs were of opaque mesh material, so that sunlight had to be directed down the length of the channels. This requirement did not present economic problems when the honeycomb was used at the receptor of a solar furnace, but the requirement of tracking made it of no advantage for flat-plate collectors. The use of transparent or aluminized materials for the honeycomb removed some of this limitation.

The ideal honeycomb material would be transparent and absorbing in the infrared. The walls of this material would allow sunlight to pass obliquely to the absorber surface, yet

they would successively absorb thermal radiation and act as a selective surface. Glass and plastic would be such materials, but cost and fragility in the first case and inadequate thermal properties in the second make them less than ideal. Aluminizing a honeycomb allows sunlight to enter at oblique angles, with the disadvantage of absorption in the multiple reflections occurring for oblique rays. The aluminized surface, however, is also infrared reflective and the mesh does not significantly reduce the infrared emission of the absorbing surface because of the high reflectance of aluminum in the infrared. If one used a selective surface coating that is highly reflective in the visible range and absorbing in the infrared, the honeycomb would function properly.

### 2.7.2 CONVECTION SUPPRESSION

A second area of potential use of honeycombs for solar applications is in the suppression of convection in collectors. When a vertical channel is made small, it has been found that the vertical convection does not begin until a certain finite temperature difference between the top and bottom of the channel is exceeded. A certain minimum Rayleigh number (Ra) must be exceeded for the onset of convection, where Rayleigh number is defined as:

$$Ra = qL^3 \rho^2 g y c_p/\mu k^2 x, \tag{3}$$

Where,

q = heat flux per unit time (W),

L = characteristic dimension, the width of the channel (m),

$y$ = volumetric expansion of the fluid ($m^3/m^3\ C^o$)

$c_p$ = specific heat of the fluid at constant pressure ($J/kg\ C^o$),

$\mu$ = dynamic viscosity ($kg/ms$),

$k$ = thermal coefficient of conductivity ($W/m\ C^o$) and

$x$ = length of the channel ($m$).

The necessity of a minimum temperature gradient for the onset of natural convection can be readily demonstrated, as Lord Rayleigh did, by heating a pan of viscous materials on a stove. The onset of natural convection, indicated by the establishment of hexagonal convection cells , does not take place as soon as heat is applied but only after a minimum heating of the bottom layers has occurred.

The theoretical minimum value for the onset of convection from a surface is when the Grashof (Gr) or Rayleigh (Ra) number is equal to 1707. The presence of the small channels of the mesh effectively increases this value of critical Gr or Ra for the surface from 1707 up to approximately 200,000 leading to the suppression of convection. However, the suppression of convection would be effective only for small temperature differences between the bottom and top of the honeycomb. If the absorber temperature rose beyond a certain minimum, then the value of q would cause the Ra value to exceed the limit and convection would begin.

The expected variation of convective heat loss with increasing temperature difference for a honeycomb is shown in Fig.2.9. Convection normally grows approximately linearly with temperature $T^{5/4}$ and is shown by the dashed line. When the

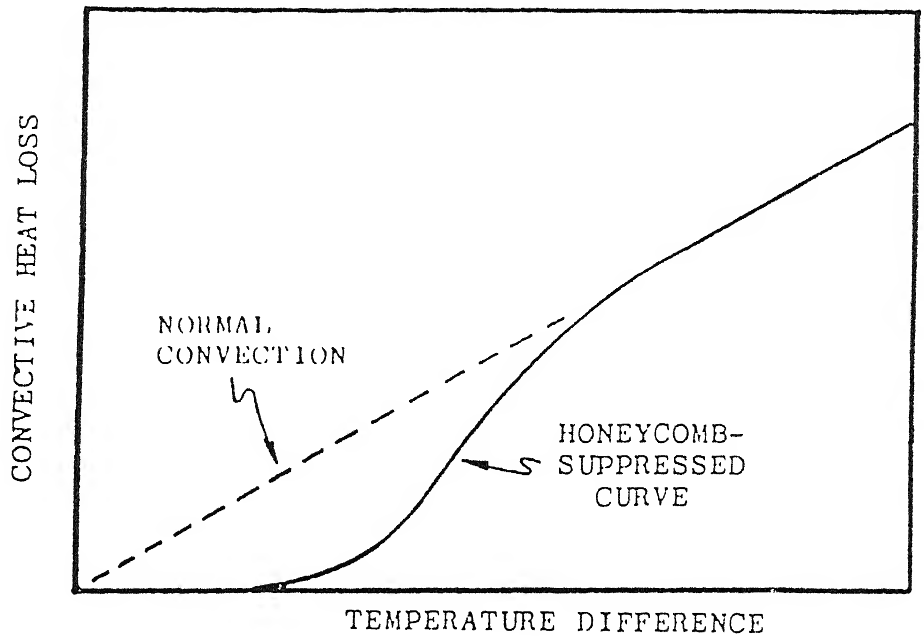



FIG. 2.9: CONVECTION SUPPRESSION WITH THE HONEYCOMB AS A FUNCTION OF THE INCREASING TEMPERATURE DIFFERENCE ACROSS IT.

Rayleigh number is sufficiently low, and when either the cell spacing or temperature difference is small, the convection will be fully suppressed. When the Rayleigh number reaches about 2000, the convection begins and it rises rapidly to reach the normal convection level.

## 2.8 CHOICE OF CELL SIZE

In choosing the cell size, the honeycomb designer must first make a design choice concerning the chief function of the honeycomb, and this differentiation on the basis of function leads to a classification of honeycombs into what may be called "large-celled" and "small-celled" honeycombs. Thus, if the honeycomb is to function purely as a convection-suppressor --the radiant suppression being provided by a low emissivity surface at one of the insulation's bounding faces-- then large-celled honeycombs, with cell sizes of the order of 12 mm in hydraulic diameter (dh), are appropriate; smaller cell sizes will still suppress convection, but they would lead to an unnecessarily large material content. Moreover, since radiant shielding is not an issue for convection suppression, the cell wall can be made arbitrarily thin. Both the larger cell and smaller wall thickness lead to a minimum plastic material content for the convection suppression honeycomb. Honeycomb insulations designed to provide radiant as well as convective suppression, on the other hand, require generally smaller cells (about 3 mm in hydraulic diameter) and thicker walls to achieve the necessary radiant shielding. They are, therefore, more intensive in their use of materials.

# CHAPTER 3

# LITERATURE SURVEY AND THE PRESENT WORK

## 3.1 LITERATURE SURVEY

The use of honeycombs and other transparent insulation materials (TIM) in solar collectors, for suppressing the frontal heat losses, has attracted the attention of many researchers over the years.

S. Sevendsen and K.I. Jensen [3,4] and A. Nordgaard and W.A. Beckman [5] report on improved flat plate collectors using aerogel tiles. Aerogel is a TIM which is strongly absorbing in the far infrared region and has a very fine structure. Consequently, neither a selective absorber nor an air gap would improve the collector's performance.

Meinel and Meninel [2] discuss both radiation and convection suppression using a general honeycomb geometry (chapter 2).

W.J. Platzer [7] reports on the total heat transport data for different plastic honeycomb type structures. He tested several honeycomb materials including Polycarbonate, Polyethylene, Polytetrafluoroethylene and Polyether-sulfone. Both the capillary and square honeycomb geometries were tested.

K.G.T. Hollands, K. Iynkaran, C. Ford and W.T. Platzer [8] gave a method for manufacturing thin walled (about 20

$\mu m$ wall thickness), large celled (about 10 mm hydraulic diameter of cell) convection suppressing honeycomb from Fluoronated ethylene propylene (FEP) plastic. The honeycomb manufacturing method used heat sealing to join adjacent strips of plastic along thin lines. The application of a small conpressive force on the strips so joined, resulted in a square honeycomb geometry. The honeycomb is sized just small enough to suppress convection. Radiation shielding was provided by a low emissivity surface at one of its bounding faces. In addition to the method of manufacturing, the measurements of the honeycomb's thermal conductance and solar transmittance were also reported. The honeycomb was seen to have a solar transmittance of 90% with a low material content of 100 to 200 $g/m^2$.

M. Rommel and A. Wagner [9] investigated two different collector systems using Transparent Insulation Materials (TIM's). The thermal and optical properties of a poly-carbonate honeycomb material were discussed with respect to the design of an improved flat plate collector. Measurements on this collector proved the good collector performance in the temperature range of 80 to 140 $^oC$. However, the honeycombs started to melt at 120 $^oC$. To overcome this problem, Rommel and Wagver also described a collector with newly developed, temperature resistant glass capillaries with which a stagnation temperature of 261 $^oC$ was measured.

M. Rommel and V. Wittwer [10] built a flat plate collector with small celled honeycombs and a selective absorber. The efficiency of this collector was seen to be comparable to

that of a vacuum tube collector (50 % efficiency at 800 $W/m^2$ and 100 K temperature difference to ambient).

K.G.T. Hollands and K. Iynkaran [12] studied a compound honeycomb collector in which an air gap was introduced between the absorber plate and the honeycomb. The performance of a flat plate solar collector combining a selective surface on the absorber plate and a plastic honeycomb in the air gap is not as high as expected because of a certain coupling between the radiation and (gaseous) conduction heat transfer modes. To decouple these modes and thereby achieve the desired low heat loss coefficient, Hollands and Iynkaran suggested leaving an air gap of about 10 mm between the absorber plate and the honeycomb -- the air gap and the honeycomb together constituting a compound honeycomb air layer (Fig. 3.1). The study demonstrated that leaving the air gap effectively decouples the modes but does not significantly alter the free convection at the design condition. It was thus concluded that the compound honeycomb collector should have a very good performance at high temperatures.

## 3.2 PRESENT WORK

From the literature survey it is apparent that transparent insulation materials, and their application to solar thermal conversion devices is still a relatively new field. This is specially true of India where very little work has been done

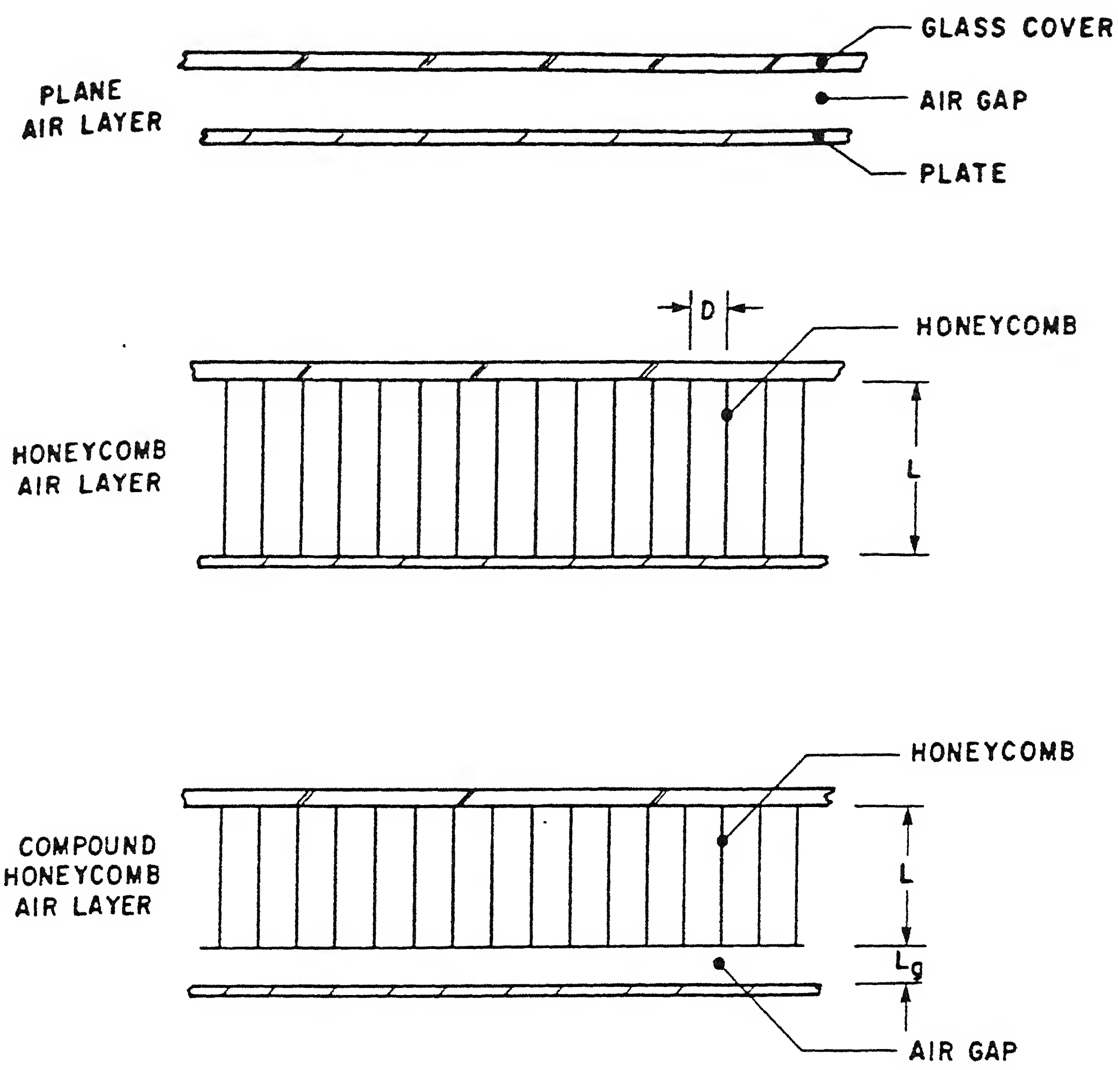



FIG. 3.1: A COMPOUND HONEYCOMB AIR LAYER.

in this rapidly developing area.

The present work involves the design, fabrication and experimentation of a flat plate solar air heater with a Polymethy- methacrylate (PMMA) or perspex honeycomb structure of 4 cm thickness situated in the absorber-glass cover air gap. Subject to the limits in the fabrication technology available, the side of the square cell of the honeycomb was taken equal to 2 cm. Thus, the effect of the honeycomb was primarily the suppression of the natural convection losses through the absorber-cover air gap, since radiation suppression requires cells of much smaller size. An air gap of 1.5 cm was introduced between the honeycomb and the absorber to prevent the coupling between the radiation and the (gaseous) conduction heat transfer modes [12] which leads to reduced performance.

To carry out a comparative evaluation of the effect of the air gap and the honeycomb on the collector's performance, it was tested for three configurations:

1. Without the honeycomb and absorber-cover air gap equal to 1.5 cm.

2. With the honeycomb of 4 cm thickness placed in the absorber-cover air gap and a layer of air of thickness 1.5 cm between the absorber and the honeycomb.

3. Without the honeycomb and absorber-cover air gap equal to 5.5 cm.

The testing in each of these configurations was carried out over a range of flow rates, under actual conditions of solar irradiation.

Efforts were made to keep the manufacturing and material costs of the collector as low as possible. For the reason, a single collector having adjustable sides was fabricated, so that it could be converted easily into each of the three configurations mentioned above. In order to ensure that testing of all the configurations was carried out under similar conditions, the experiments were performed in the months of May-June when the solar radiation incident on the collector was approximately constant.

# CHAPTER 4

# EXPERIMENTAL SET-UP AND TEST PROCEDURE

## 4.1 COLLECTOR DESIGN AND FABRICATION

The experiment involves the design, fabrication and performance evaluation of a flat plate solar air heater with honeycomb transparent insulation. To determine the effect of the honeycomb, which is made of Polymethyl methacrylate (PMMA) or perspex, on the frontal heat losses of the collector, a comparative analysis has been carried out. To do so, the collector has been tested in three configurations.

1. Without the honeycomb ,and absorber glass cover air gap equal to 1.5 cm.

2. With the square celled (side 2 cm) perspex honeycomb of thickness 4 cm placed between the absorber and glass cover.

3. Without the honeycomb, and absorber - glass cover air gap equal to 5.5 cm.

The first step in this process involved the designing and fabrication of the collector with adjustable absorber glass cover air gap.

### 4.1.1 CHOICE OF THE MATERIALS

The main components of the collector are:

1. Absorber plate
2. Cover plate
3. Honeycomb
4. Insulation
5. Casing

The absorber plate is usually made of copper, steel, aluminum or plastic. The choice of the material depends on the conductivity and heat transfer coefficients required. Air collector absorber plates are not required to have high thermal conductivity because the air comes into direct contact with the entire surface. Galvanized iron has sufficiently high conductivity, is inexpensive and is readily available in the local market. Considering these factors, galvanized iron sheet has been chosen as the material for the absorber plate.

The cover plate used for the collector was made of simple window glass of 4 mm thickness. Glass is the most commonly used cover material. It has a high transmittance (of the order of 0.85 or more) in the short wavelength range and is practically opaque to longwave infrared radiation emitted by the absorber plate. Glass deteriorates negligibly even over very long periods of exposure to intense ultraviolet radiation.

The honeycomb was fabricated of 3 mm thick Polymethyl - methacrylate (PMMA) commonly known as perspex. Perspex sheets

were chosen for several reasons. Firstly, perspex is transparent to solar radiation. Secondly, being relatively soft, it could be conveniently fabricated into a square celled honeycomb geometry. Thirdly, it is comparatively inexpensive and also readily availably in the local market. Also, not much work has been done previously on perspex honeycomb structures.

Several types of insulation are used in collectors to minimize the heat loss from the back and the sides. The commonly used materials are Fiberglass, Ceramic fibre blanket, Mineral fibre blanket, Calcium silicate foam, Urea formaldehyde foam, Poly-urethane foam and Glass wool. Glass wool was chosen since it is inexpensive and easily available.

The material chosen for the casing was a galvanized iron sheet of 24 gauge thickness because of its low cost, easy availability and high corrosion resistant property.

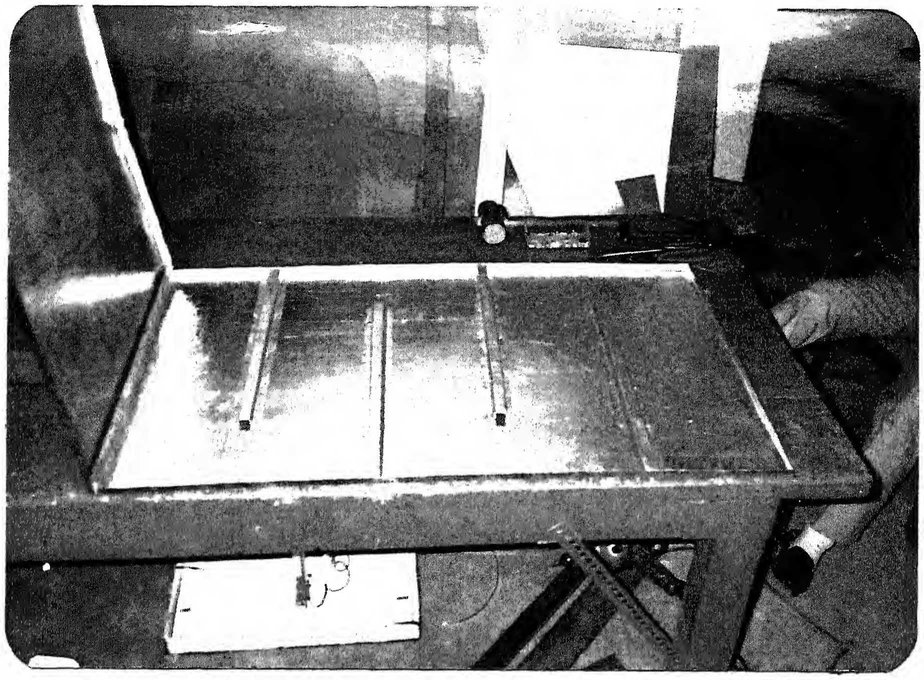
### 4.1.2 FABRICATION OF INDIVIDUAL COMPONENTS

The fabrication of the collector was done in several stages. To begin with, the absorber plate was fabricated out of a single 8'x3' galvanized iron sheet of 24 gauge thickness. The geometry chosen was a retangular box of dimensions 114x69x1.5 cm. Channels were provided inside the absorber plate at regular interval so as to facilitate the serpentine movement of air within it (Photograph 4.1). This was essential in order to achieve a substantial increase in its temperature. The absorber plate was made leakage proof using m-seal. Two holes were drilled in the

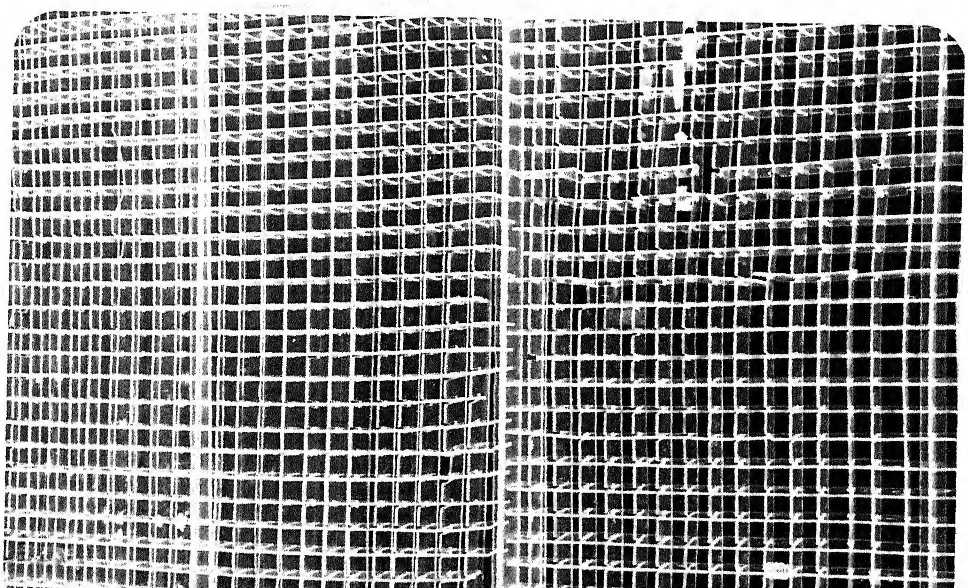
sides at diagonally opposite ends. The inlet and outlet pipes were fixed over these holes by brazing. The upper surface of the absorber plate was painted dull- black using a mixture of black paint and black oxide. Thermocouples were provided at regular intervals along the path of flow of the air within the absorber plate.

The collector housing was also made of galvanized iron sheets. It was in the shape of an open topped rectangular box of dimensions 120x75x10 cm. Galvanized iron strips of 4 cm thickness were fabricated for increasing the depth of the housing while testing with the honeycomb situated between the absorber plate and the glass cover.

The honeycomb was fabricated out of 6'x3' perspex sheets of 3 mm thickness. Of the two possible honeycomb geometries shown in Fig 4.1 ,the square celled geometry was chosen. The side of an individual cell was taken equal to 2 cm and the thickness of the honeycomb was 4 cm. The fabrication of the honeycomb was carried out by cutting the perspex sheets into strips of 4 cm thickness. Several such strips were clamped together and slots were cut into them upto a depth of 2 cm using a three blade hacksaw. Finally, the honeycomb was assembled by fitting the slots of each of the strips into one another. Photograph 4.2 shows a view of the honeycomb fabricated in this fashion.



PHOTOGRAPH 4.1: ABSORBER PLATE SHOWING CHANNELS FOR SERPENTINE MOVEMENT OF AIR.



PHOTOGRAPH 4.2: A VIEW OF THE HONEYCOMB.

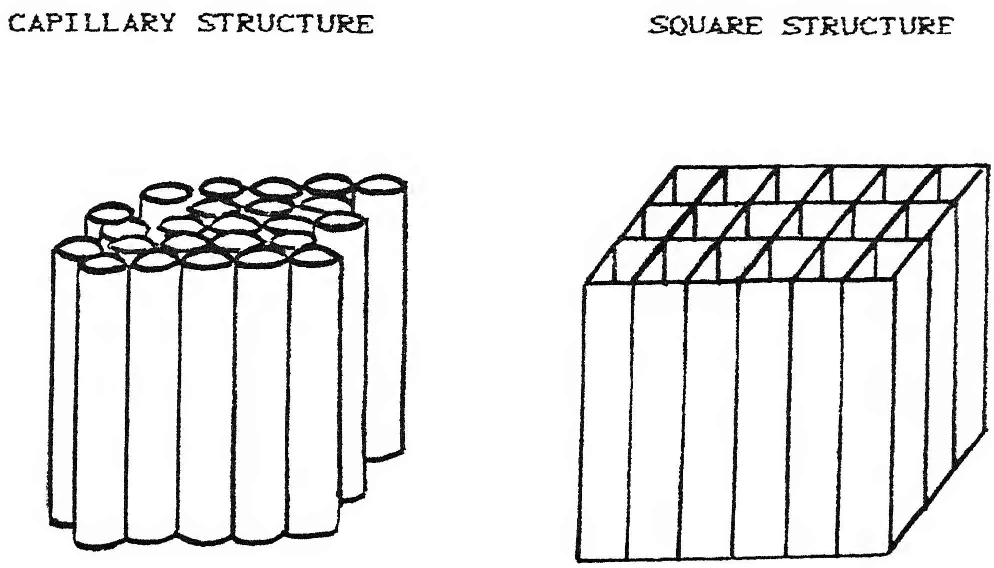



FIG. 4.1: SKETCH OF TWO BASIC HONEYCOMB GEOMETRIES.

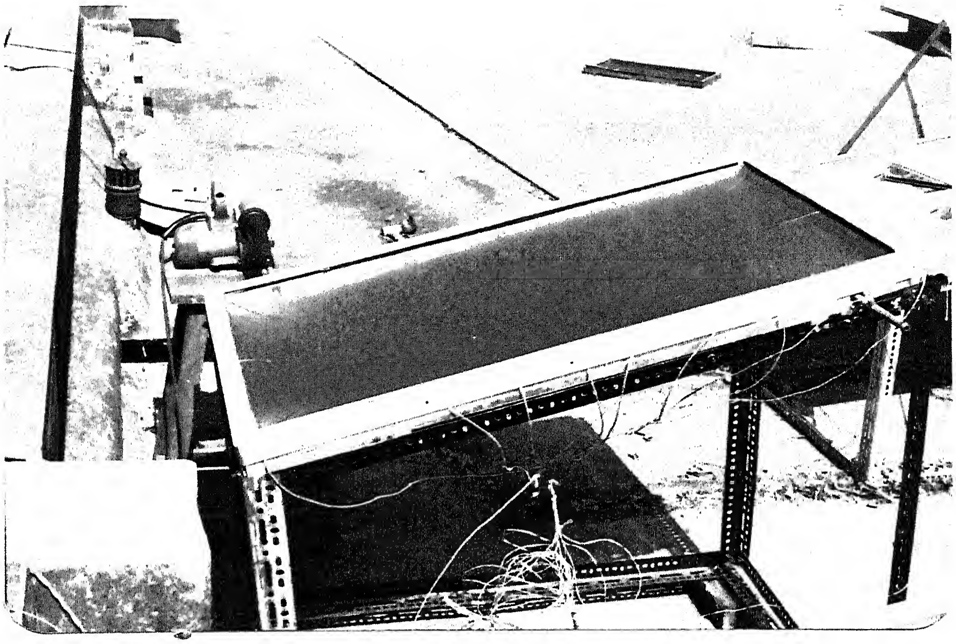
### 4.1.3 ASSEMBLY OF THE COLLECTOR

The collector was initially assembled without the honeycomb and absorber-glass cover air gap equal to 1.5 cm. The bottom and sides of the housing were filled with glass wool insulation of thickness 3 cm. The absorber plate was then placed inside the housing on wooden block supports.

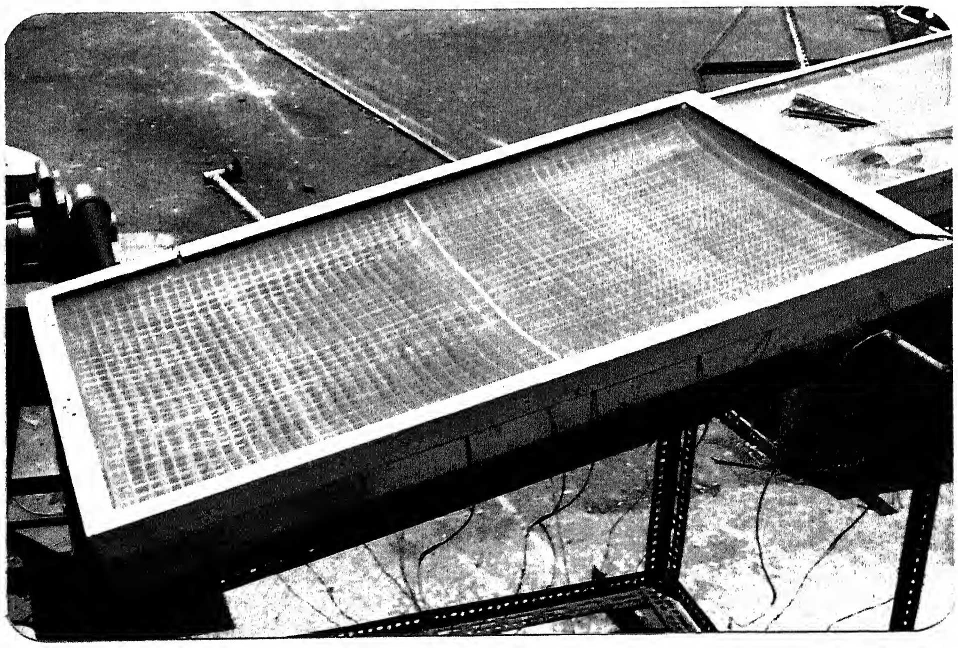
The cover glass was placed on the supports provided for the purpose and fastened, using one and a half inch aluminium angles. While fixing the glass care was taken to keep adequate clearance to provide for differential expansion between the glass plate and other collector components. To prevent the breakage of glass due to vibrations and to make the collector waterproof , a rubber bedding was used all around the edges of the glass plate before fastening with the aluminium angles. The stand for the collector was made from slotted iron angles. The angle of tilt chosen was $12^{o}$. Photograph 4.3 shows a view of the collector mounted on the roof.

While testing with the honeycomb, the depth of the casing was increased by fastening the 4 cm strips all around. The honeycomb was placed in the absorber-glass cover air gap over small wooden supports so that any shadowing effect was negligible. (Photograph 4.4 and Fig. 4.2).

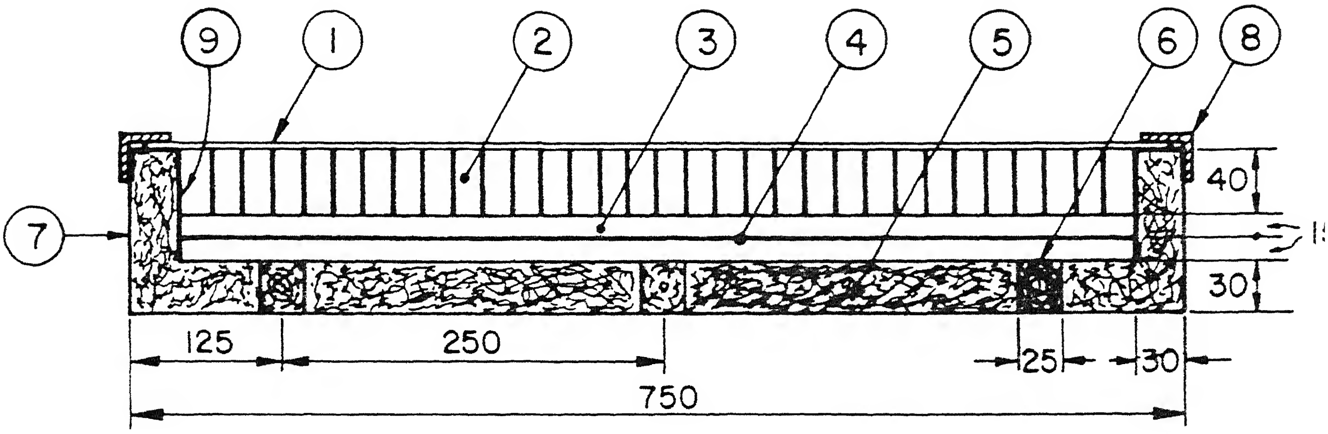
In the third stage of experimentation, the honeycomb was removed but the absorber-glass cover air gap was kept as such i.e.,equal to 5.5 cm.



PHOTOGRAPH 4.3: PLAIN COLLECTOR MOUNTED ON THE ROOF.



PHOTOGRAPH 4.4: HONEYCOMB COLLECTOR MOUNTED ON THE ROOF.




NOT TO SCALE

1. Glass Pane (4)
2 Perspex Honeycomb (40)
3 Air Gap (15)
4 Collector ( Absorber plate)
5 Glass Wool Insulation (30)
6 Wooden Blocks
7 G.I Sheet Casing
8 Aluminium Angle Frame (38 x 38 x 4)
9 Channel for Supporting Glass Cover

Note : All dimensions are in mm

FIG. 4.2: AN IMPROVED FLAT PLATE AIR HEATER WITH HONEYCOMB TRANSPARENT INSULATION.

## 4.2 INSTRUMENTATION

### 4.2.1 TEMPERATURE MEASUREMENT

To measure the temperature at various points along the flow-path of air, copper- constantan thermocouples together with a digital millivoltmeter have been used. The millivoltmeter shows the thermo-emf corresponding to the temperature of the thermocouple bead. This thermo-emf can be converted into its corresponding temperature value using the standard calibration chart for copper constantan thermocouples.

To facilitate multi channel temperature measurements, two eight point rotary switches have been used. These switches connect different thermocouples to the millivoltmeter as the knob is rotated.

### 4.2.2 FLOW RATE MEASUREMENT

The experiment was conducted for four different air flow rates. The flow rate was changed by changing the voltage input to the blower using a rheostat.

The measurement of the flow rate was done by measuring the average velocity in the exit pipe. A vane anemometer was used for the purpose. The anemometer chosen was of the same size as the exit pipe so that it directly gave the average velocity in the pipe cross section. The readings of the anemometer were fed into a digital velocity indicator which automatically gave the time averaged velocity in m/s units. Finally, knowing the exit pipe

diameter, it was possible to determine the air flow rate through the collector. This process was carried out for all the rheostat settings for which the experiment was conducted. Fig. 4.3 shows the variation of the air flow rate with the voltage input to the blower.

### 4.2.3 SOLAR RADIATION DATA

Solar radiation data published by Mani [1] was used for the month of May, Data given for Jodhpur was used as Jodhpur is situated at almost the same latitude as Kanpur i.e., 26.3 $^{o}$N. The experiment was conducted only on clear days to overcome the influence of cloudiness on the incident solar radiation.

## 4.3 TEST PROCEDURE

The cover glass plate was wiped with a clean piece of cloth twice each day, so as to ensure that no dust remained on the collector. The experiment was conducted on the three configurations mentioned in Section 4.1 for different air flow rates. The temperature readings were taken at regular intervals from 6 am to 6 pm each day at the following locations:

(a) collector inlet

(b) collector outlet

(c) along the air-flow path within the absorber plate

(d) room temperature.

Photograph 4.5 shows a view of the test bench.

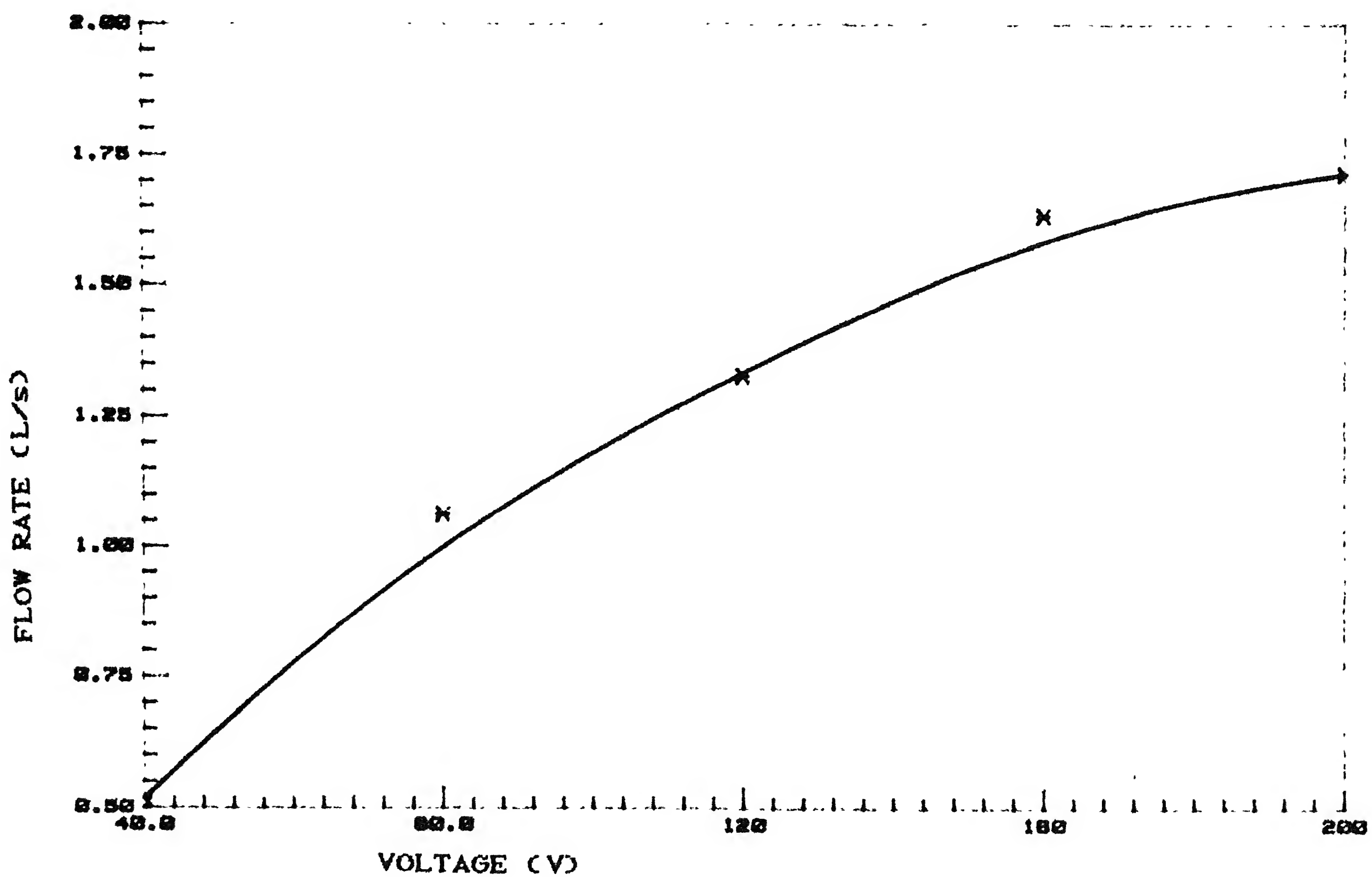



FIG. 4.3: VARIATION OF FLOW RATE WITH VOLTAGE INPUT TO THE BLOWER.

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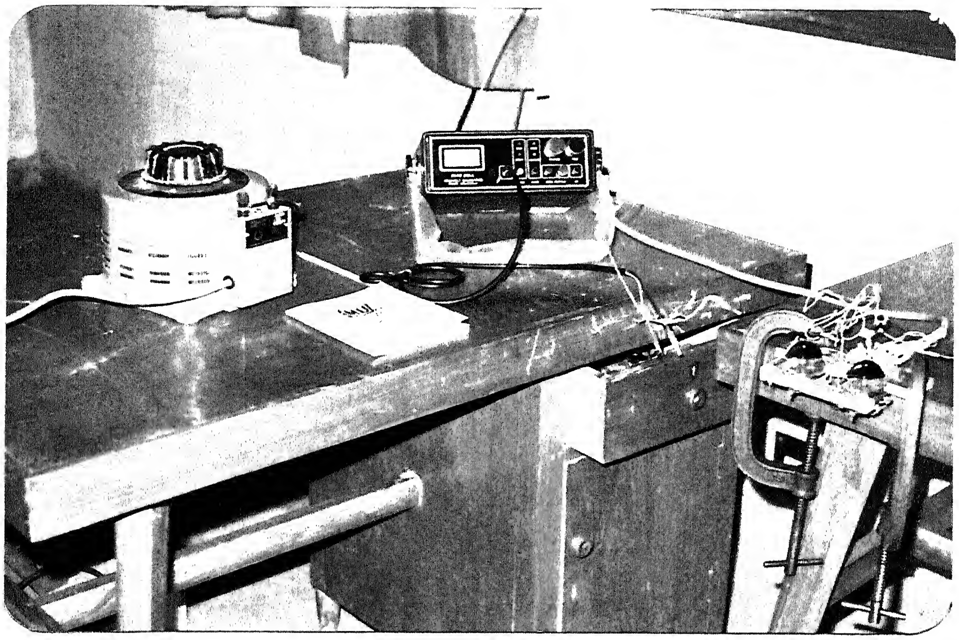

PHOTOGRAPH 4.5: THE TEST BENCH.

# CHAPTER 5

# RESULTS, DISCUSSION AND CONCLUSIONS

## 5.1 RESULTS AND DISCUSSION

The flow rate of air through the collector as a function of the voltage input to the blower was calculated by measuring the average velocity of air in the exit pipe using a vane anemometer and a digital velocity indicator. Knowing the exit velocity and the pipe diameter, it was easy to calculate the flow rate. The variation of the flow rate with the blower voltage has already been shown in Fig. 4.3 of the previous chapter.

The variation of the inlet and outlet air temperature with the hour of the day was recorded for air flow rate equal to 0.516, 1.062, 1.328 and 1.632 L/s for all the collector configuration i.e.

| | | | |
|---|---|---|---|
| 1. | Plain collector | with air gap between absorber plate and glass cover equal to 1.5 cm | Configuration 1 |
| 2. | Honeycomb | with 4 cm of collector collector honeycomb transparent insulation in the air gap of 5.5 cm between absorber plate and glass cover | Configuration 2 |
| 3. | Plain collector | with air gap between absorber plate and glass cover equal to 5.5 cm | Configuration 3 |

Also, the variation of air temperature along the flow path was recorded for all the above collector geometries and condition.

Figure 5.1 to 5.3 show the variation of the inlet and the outlet air temperatures with the hour of the day for flow rate equal to 0.516 L/s, for the plain collector without honeycomb and absorber-glass cover air gap equal to 1.5 cm. Similarly , figure 5.2 and 5.3 correspond to results for the honeycomb collector and for the plain collector with absorber-glass cover air gap equal to 5.5 cm, respectively. A comparison of the three curves shows that the maximum outlet air temperature of about 124.1 $^{o}$C, corresponding to an inlet at 49.2 $^{o}$C, is obtained in the case of the honeycomb collector. Configuration 3 gives an intermediate outlet air temperature of 116.3 $^{o}$C with inlet at 48.7 $^{o}$C. Configuration 1 results in the least outlet air temperature of 110.4 $^{o}$C, corresponding to an inlet at 51.8 $^{o}$C.

These results show that the maximum temperature gain occurs in the case of the honeycomb collector (74.9 $^{o}$C), while the least in case of the plain collector with the absorber-glass cover air gap equal to 1.5 cm (58.6 $^{o}$C). Increasing the air gap to 5.5 cm results in an increase in the temperature gain of the air (67 $^{o}$C).

Figures 5.4 to 5.6 relate to air flow rate through the collector equal to 1.062 L/s for all the three configurations. As can be seen from the figures, configuration 1 gives the least gain in air temperature (56.6 $^{o}$C), configuration 2 gives the greatest gain in air temperature (67.6 $^{o}$C) while the configuration 3 gives

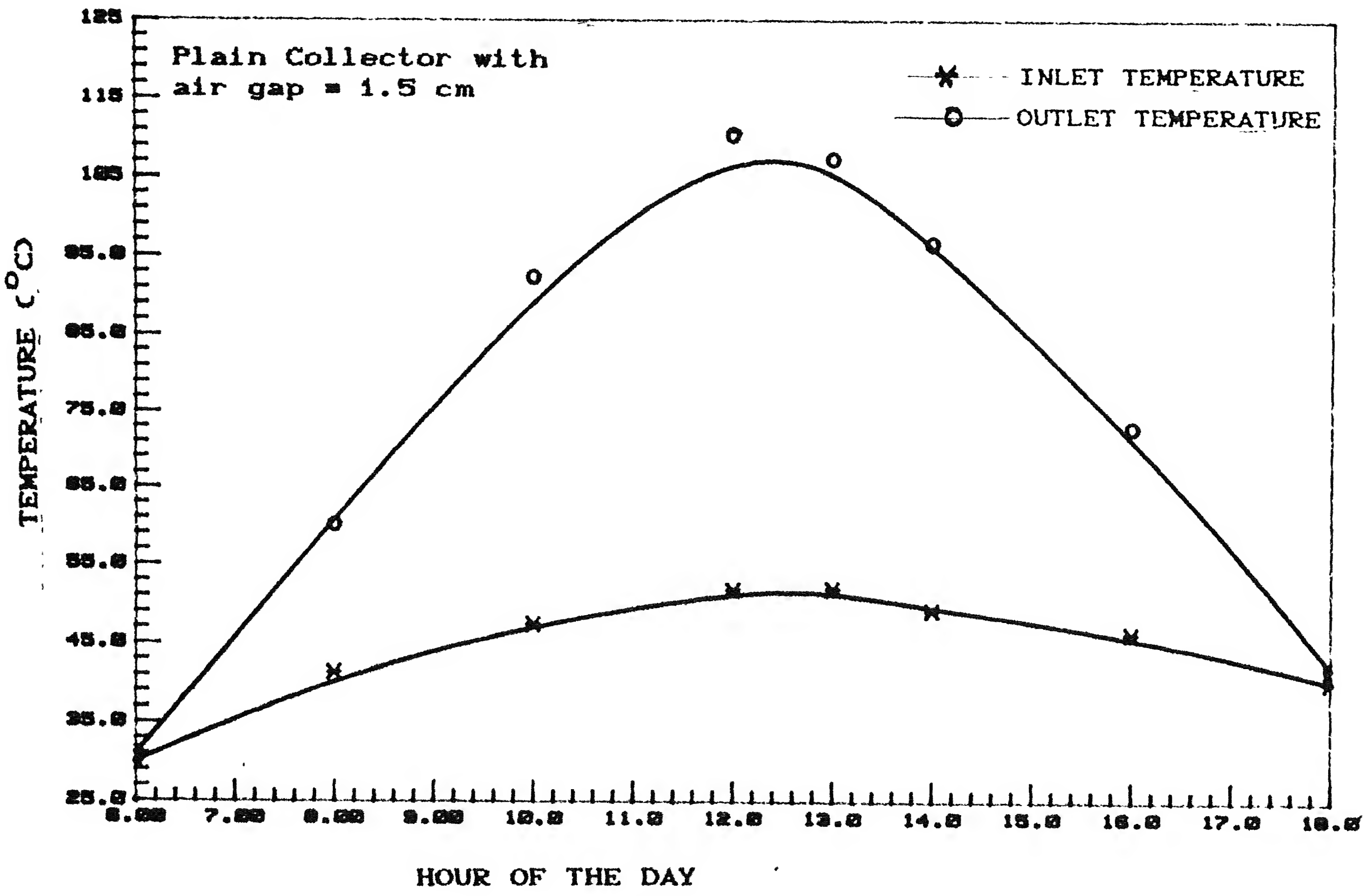


FIG. 5.1: AIR TEMPERATURE (FLOW RATE = 0.516 L/s).

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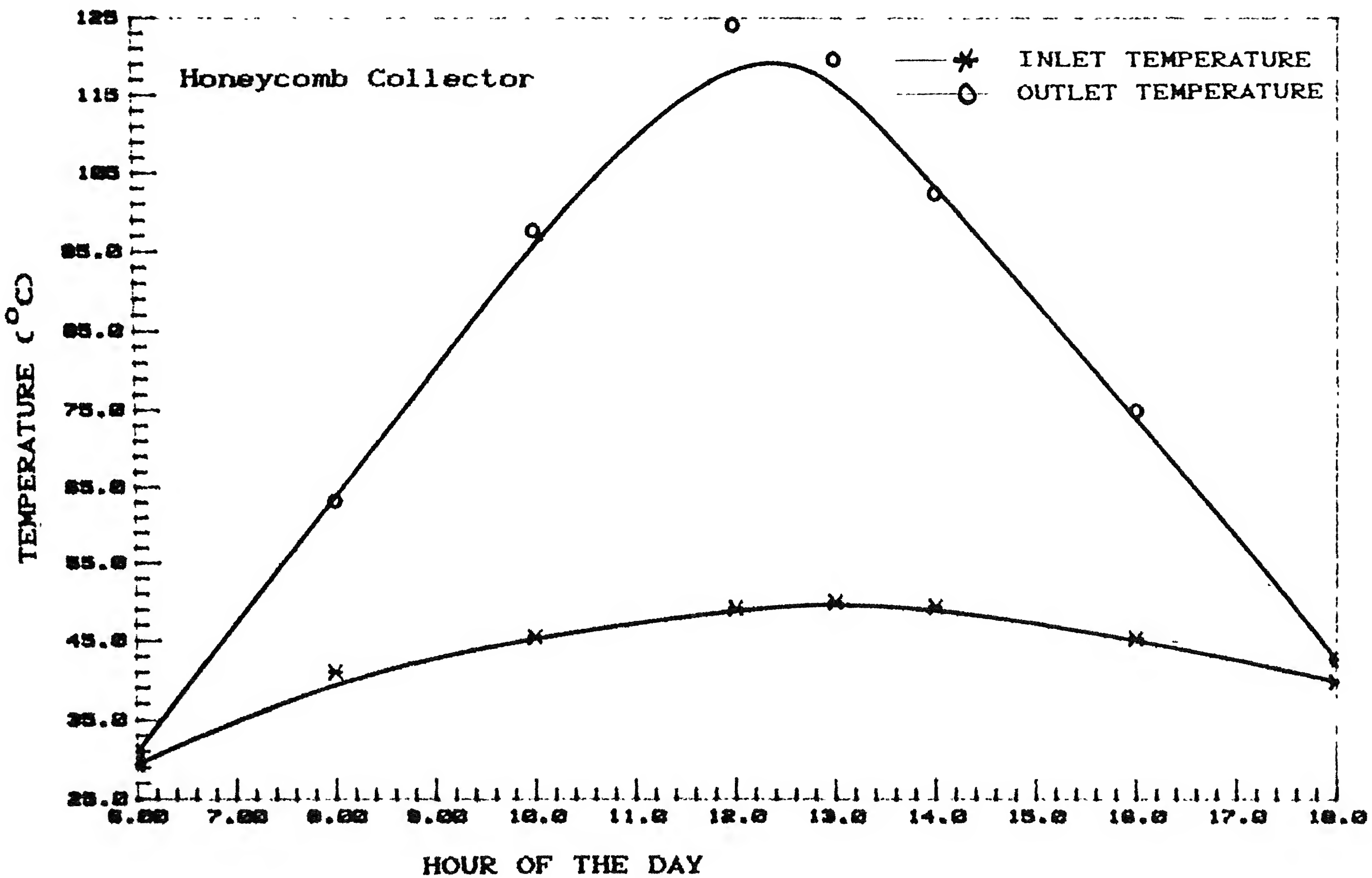


FIG. 5.2: AIR TEMPERATURE (FLOW RATE = 0.516 L/s).

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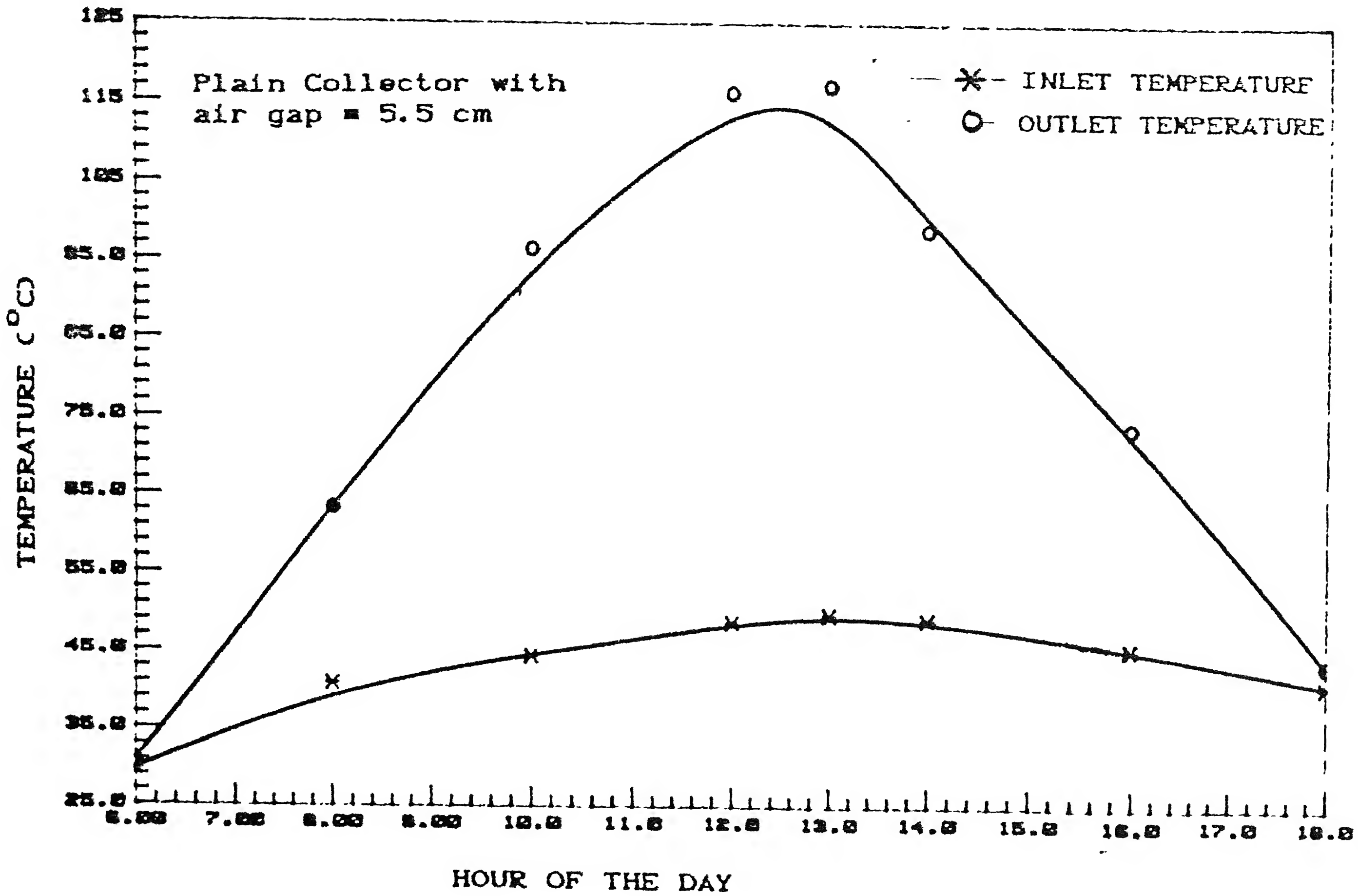


FIG. 5.3: AIR TEMPERATURE (FLOW RATE = 0.516 L/s).

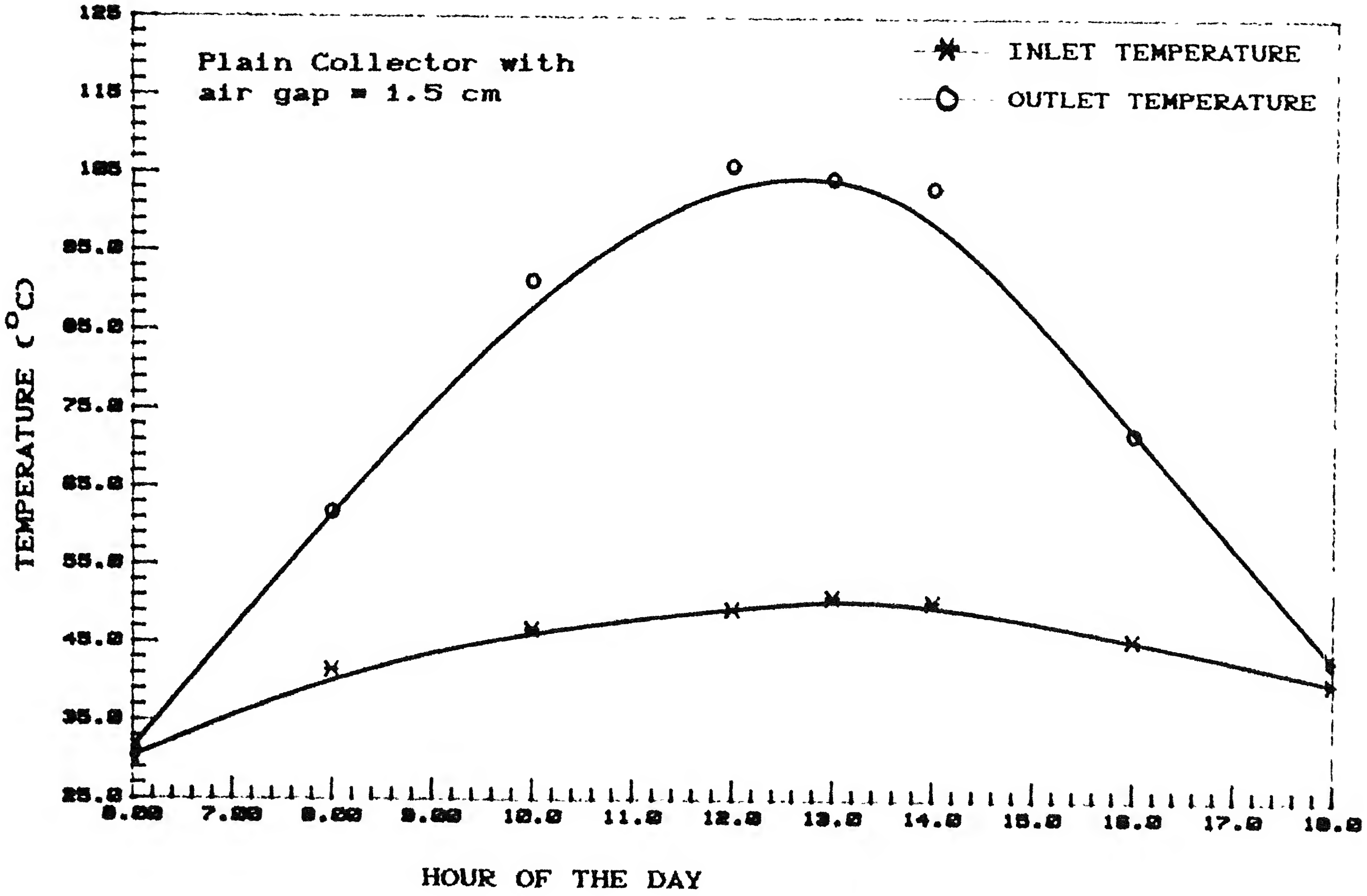


FIG. 5.4: AIR TEMPERATURE (FLOW RATE = 1.062 L/s).

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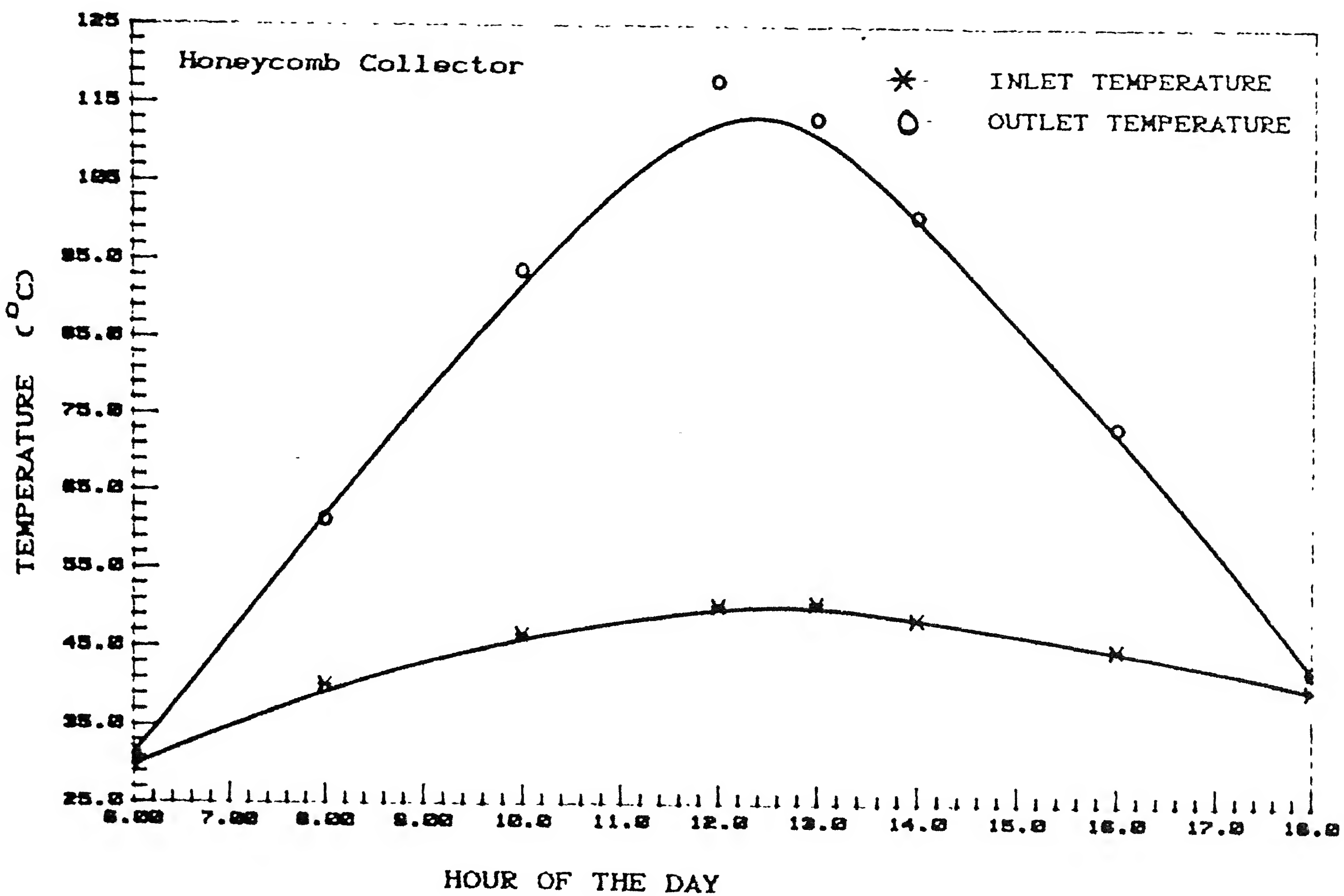


FIG. 5.5: AIR TEMPERATURE (FLOW RATE = 1.062 L/s).

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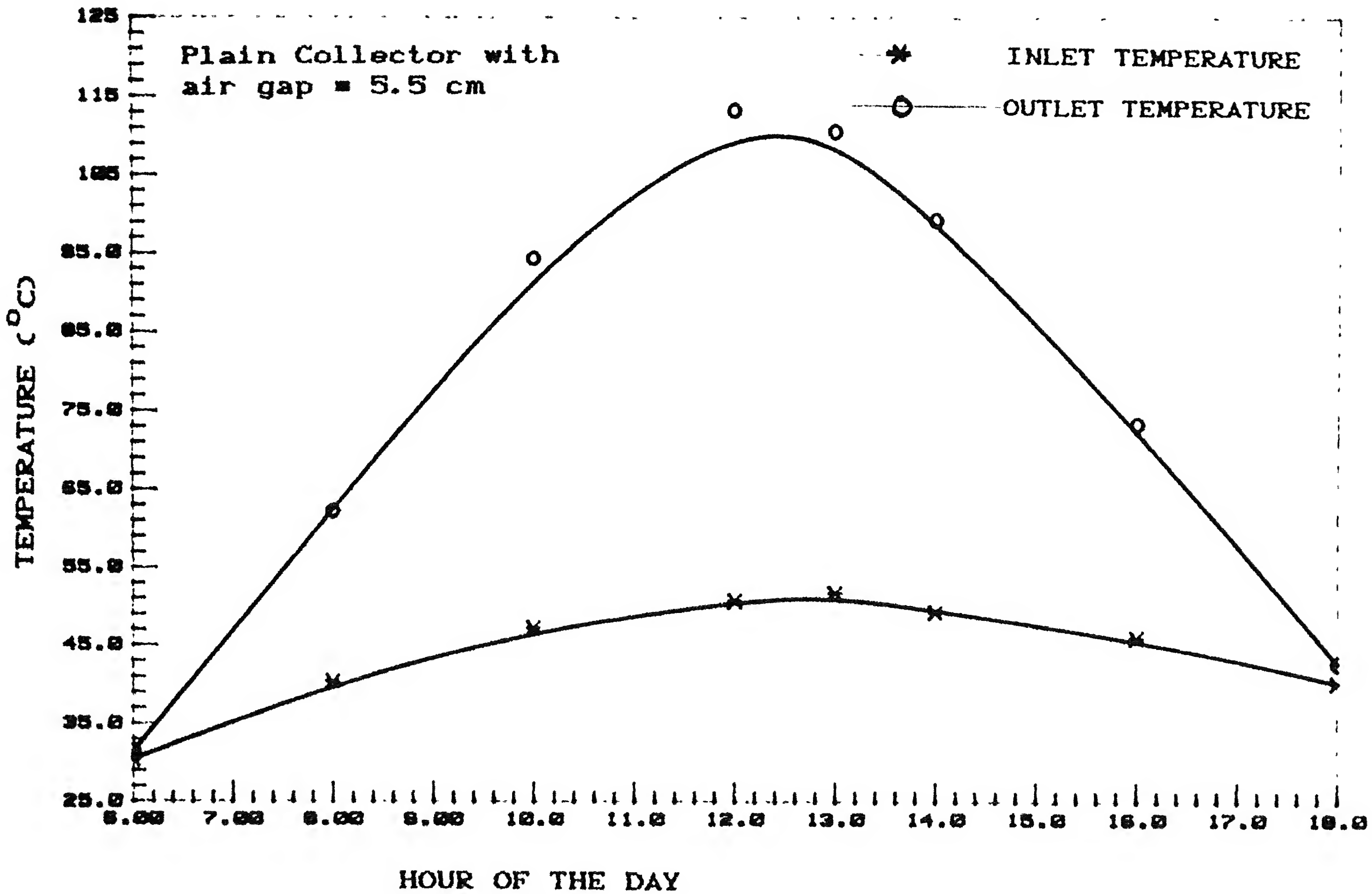


FIG. 5.6: AIR TEMPERATURE (FLOW RATE = 1.062 L/s).

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intermediate results (62.6 $^{o}$C). These results are in complete agreement with Figures5.1 to 5.3. Another discernible trend is that increasing the flow rate results in a decrease in the outlet air temperature, as can be readily seen by comparing Fig. 5.1 with 5.4, Fig. 5.2 with 5.5, and Fig. 5.3 with 5.6.

Fig. 5.7 to 5.9 refer to the above three configurations with the air flow rate through the collector equal to 1.328 L/s. As in the previous cases, the honeycomb collector (Fig. 5.8) again gives the maximum outlet air temperature (116 $^{o}$C) and the maximum temperature gain (65.5 $^{o}$C). The temperature gain is however, less than that of Fig. 5.5 which corresponds to the flow rate of 1.062 L/s. A similar trend is also followed for the collector in configurations 1 and 3, with configuration 3 resulting in a greater temperature gain (61 $^{o}$C) as compared to that obtained in configuration 1 (55.6 $^{o}$C).

Finally, Figures 5.10 to 5.12 have been drawn for the air flow rate equal to 1.632 L/s for the three collector configurations. Here again, the honeycomb collector results in the maximum temperature gain (64.0 $^{o}$C) while the plain collector with absorber-glass cover air gap equal to 1.5 cm results in the least temperature gain (56.3 $^{o}$C) . Also, within the limits of experimental accuracy , it can be easily observed that the temperature gain in all the three collector configurations for the maximum flow rate is, less than that for other flow rates, as expected.

It is thus evident that for all the flow rates, the collector with honeycomb transparent insulation (configuration 2) results in

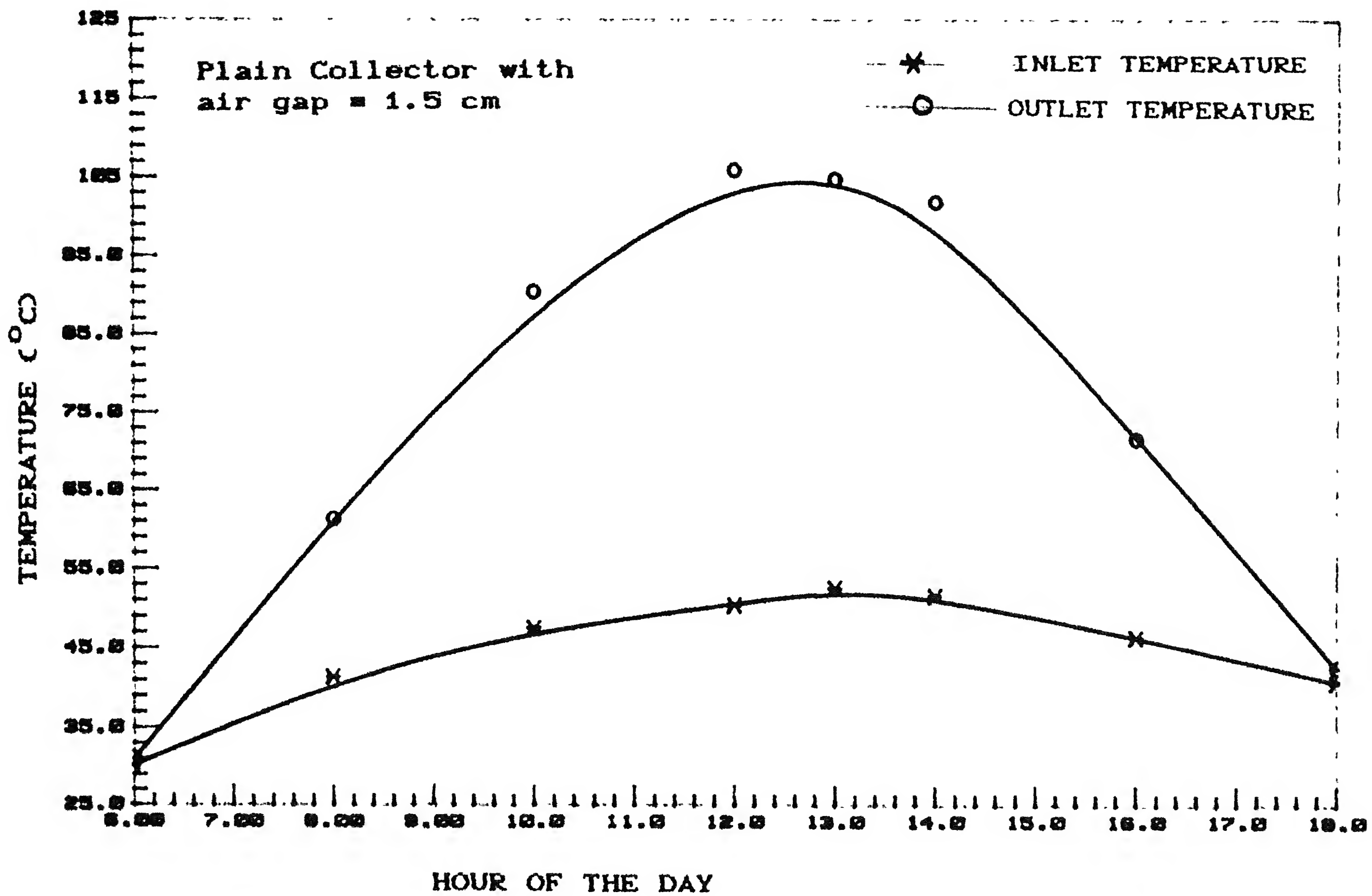


FIG. 5.7: AIR TEMPERATURE (FLOW RATE = 1.328 L/s).

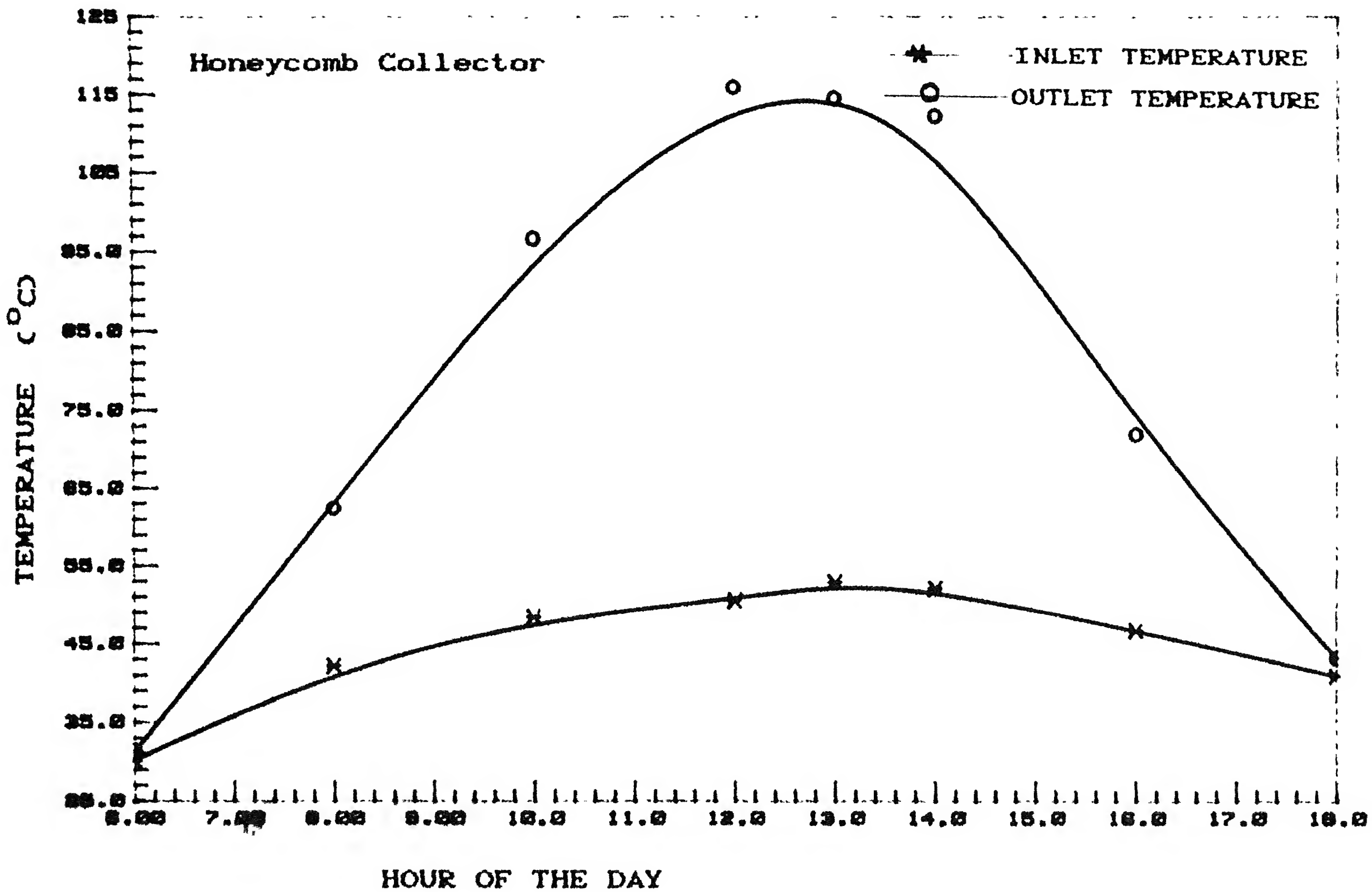


FIG. 5.8: AIR TEMPERATURE (FLOW RATE = 1.328 L/s).

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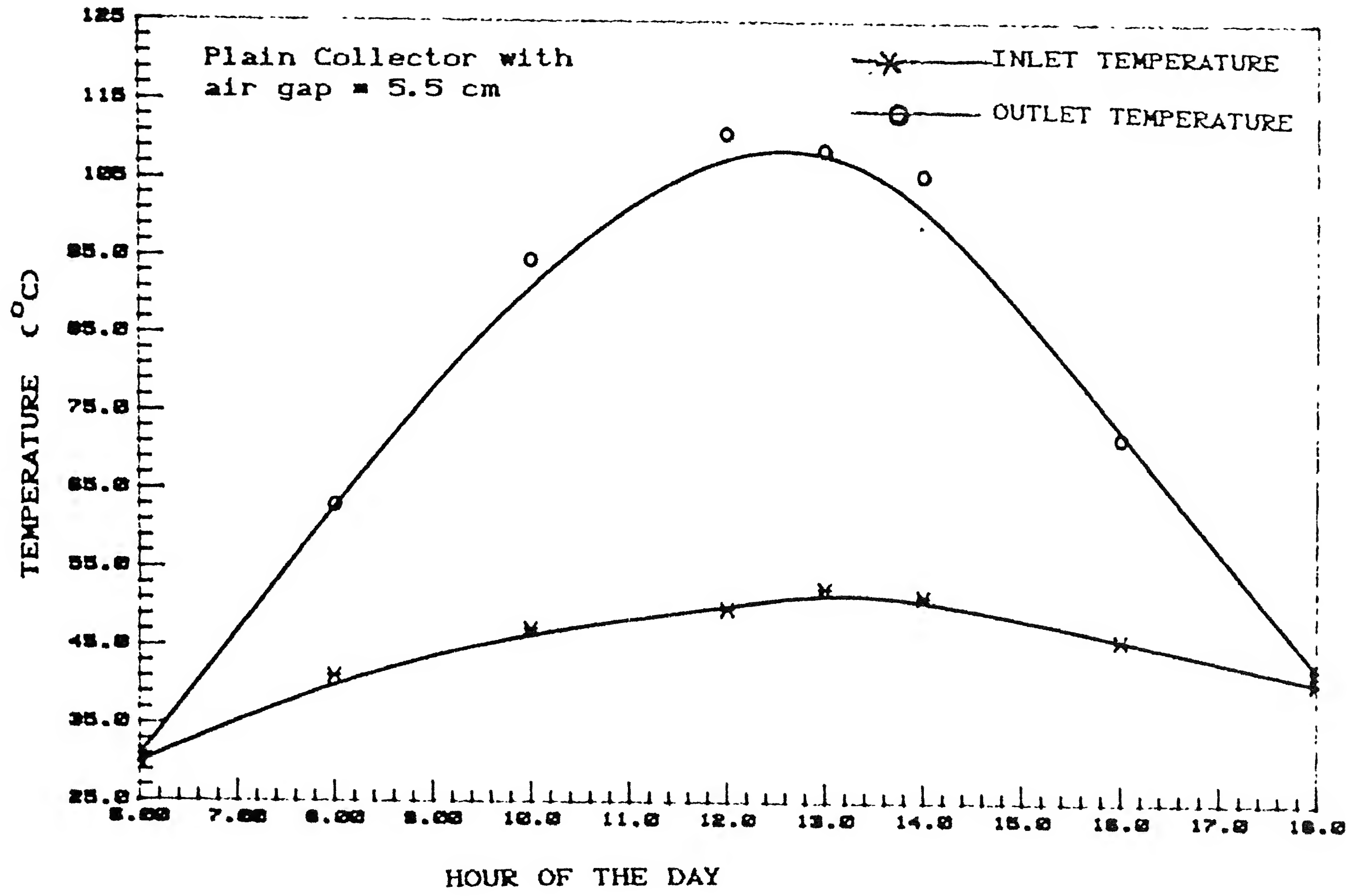


FIG. 5.9: AIR TEMPERATURE (FLOW RATE = 1.328 L/s).

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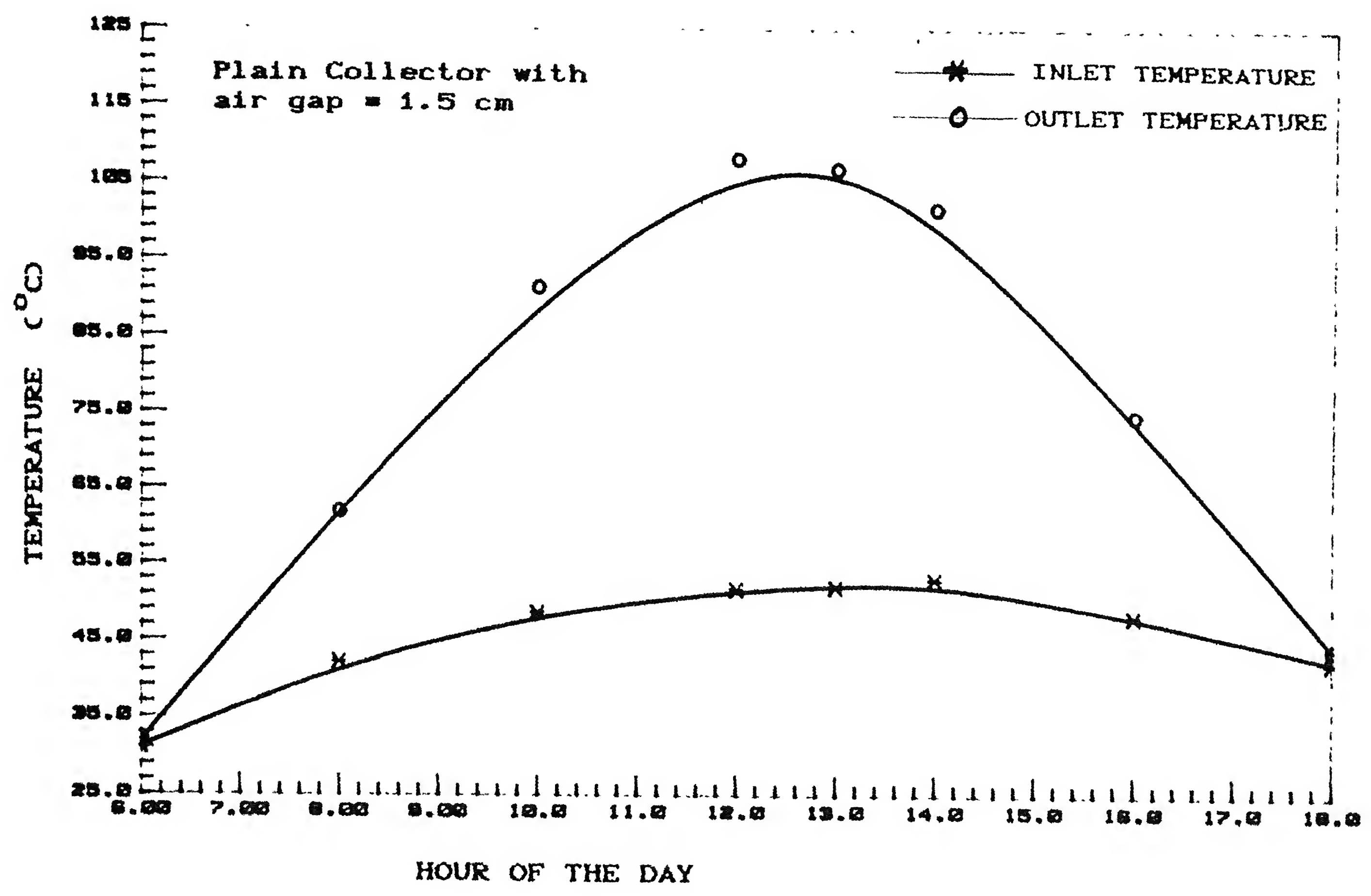


FIG. 5.10: AIR TEMPERATURE (FLOW RATE = 1.632 L/s).

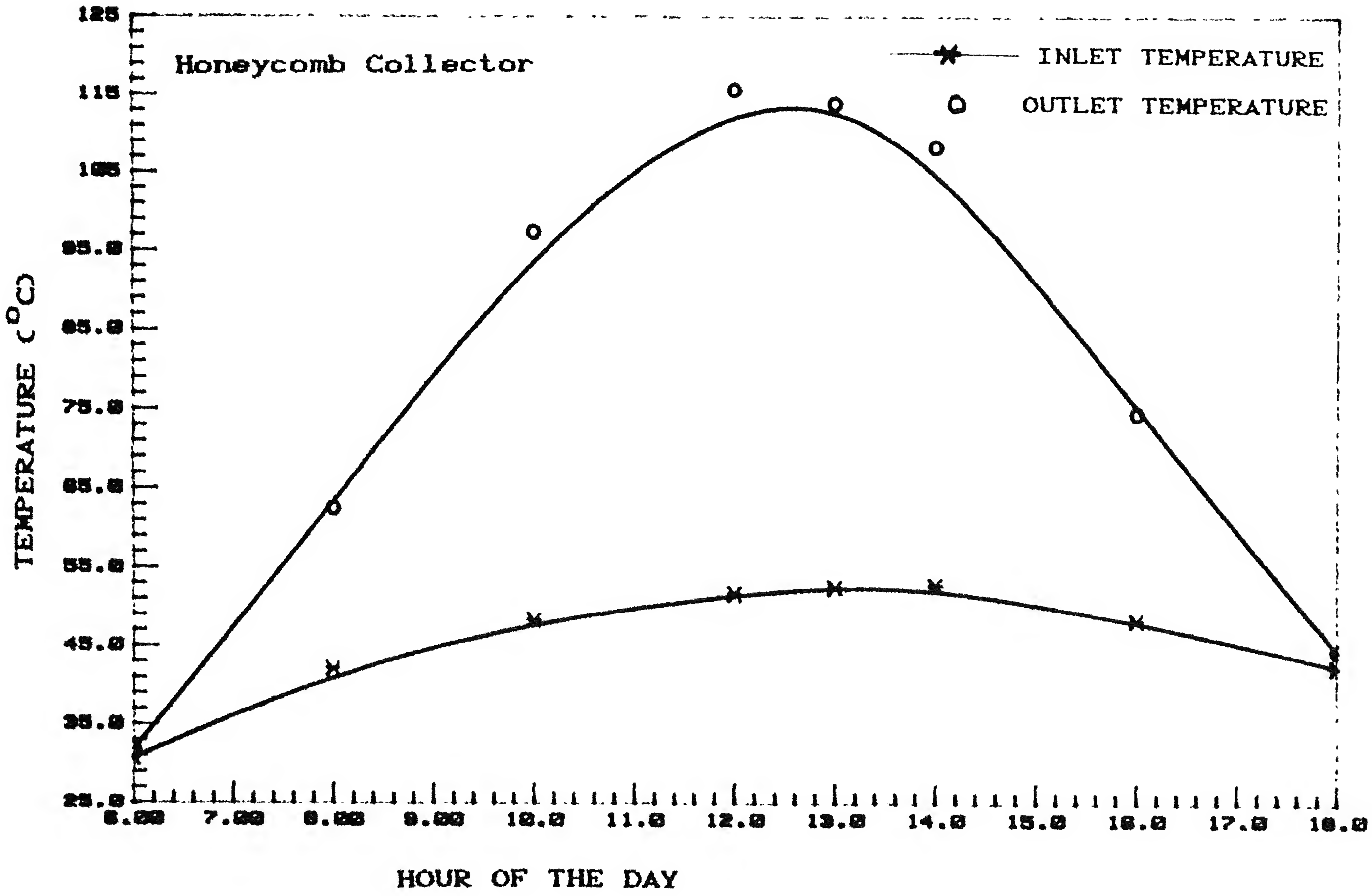


FIG. 5.11: AIR TEMPERATURE (FLOW RATE = 1.632 L/s).

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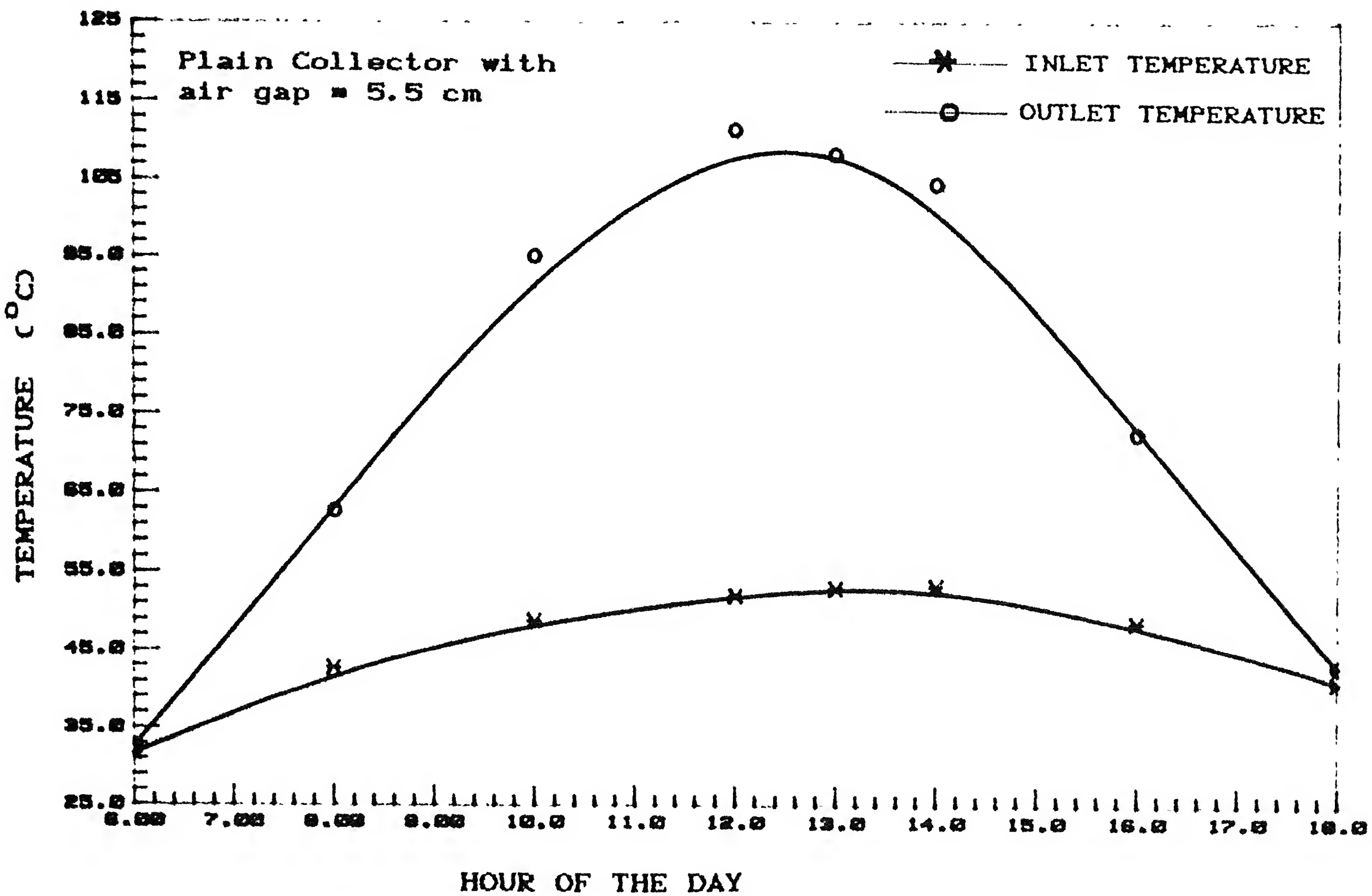


FIG. 5.12: AIR TEMPERATURE (FLOW RATE = 1.632 L/s).

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the largest temperature gain of the air. This shows that the honeycomb effectively reduces the frontal heat losses of the collector. In fact, it is mainly the losses due to the natural convection in the absorber-glass cover air gap which are suppressed (see Sec. 2.7.2) by the honeycomb structure. The radiative losses are not suppressed by the honeycomb cells because they are not sized small enough to bring about any meaningful reduction in the radiative losses (Sec. 2.8).

It is observed from a comparison of results for the plain collector with different air gaps that the temperature gain increases significantly with increasing the absorber-glass cover air gap. This may be due to the fact that increasing the air gap brings about a reduction in the radiative losses, since the thicker layer of air absorbs more of the outgoing longwave radiation emitted by the absorber plate. Also, the onset of natural convection is somewhat delayed in the thicker air layer (5.5 cm thickness) since the temperature gradient within it is lesser as compared to that in the thinner air layer (1.5 cm thickness). This is in agreement with the fact that the onset of natural convection in a fluid requires a certain minimum temperature gradient across it, as was demonstrated by Lord Rayleigh [2]. These two factors more than compensate for a slight decrease in the radiation incident on the absorber plate with the increasing air gap. It can, thus, be concluded that higher air temperatures and temperature gains can be achieved simply by using a plain collector with larger air gap, even though it would not be as efficient as a honeycomb collector.

Fig. 5.13 shows the variation of the collector efficiency with the air flow rate. The collector efficiency is defined as the ratio of the net heat gained by the air to the net energy incident on the absorber plate (Appendix A). To compare the performance of the collector in the each of the three configurations, all the three curves are drawn on the same set of coordinate axes. As can be readily seen, the efficiency for a particular configuration increases almost linearly with the flow rate of air. The low value of the efficiencies (maximum 12.4%) obtained are due to the fact that the air flow rates used in the experiment are very small. This was, however, done to magnify the effect of the honeycomb on the collector temperatures with low air flow rates. The nature of the efficiency curves indicates that increasing the flow rate would result in greater collector efficiencies.

It is also evident, that the honeycomb collector gives the greatest value of the efficiency for all the flow rates for which the experiment was conducted. The plain collector with absorber-glass cover air gap equal to 5.5 cm gives intermediate values of the efficiency while the collector with absorber-glass cover air gap equal to 1.5 cm is the least efficient for all flow rates.

Fig. 5.14 plots the variation of the air temperature along the collectors' length at 12:00 hours and for a flow rate of 0.516 L/s. It can be readily seen from these plots, that the rate of increase of air temperature falls rapidly with the collector length, with the greatest increase in temperature occurring in the

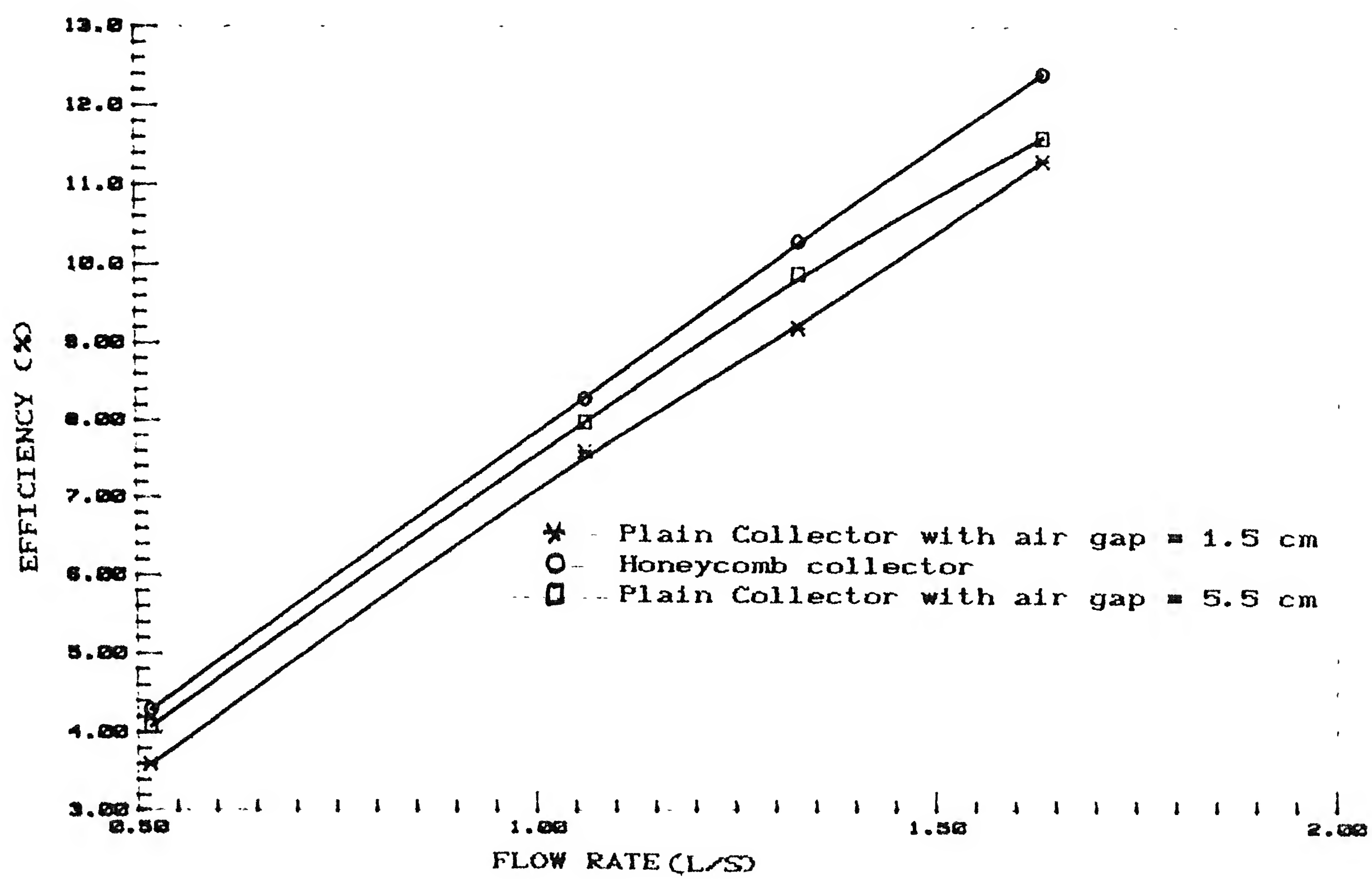


FIG. 5.13: VARIATION OF COLLECTOR EFFICIENCY WITH FLOW RATE.

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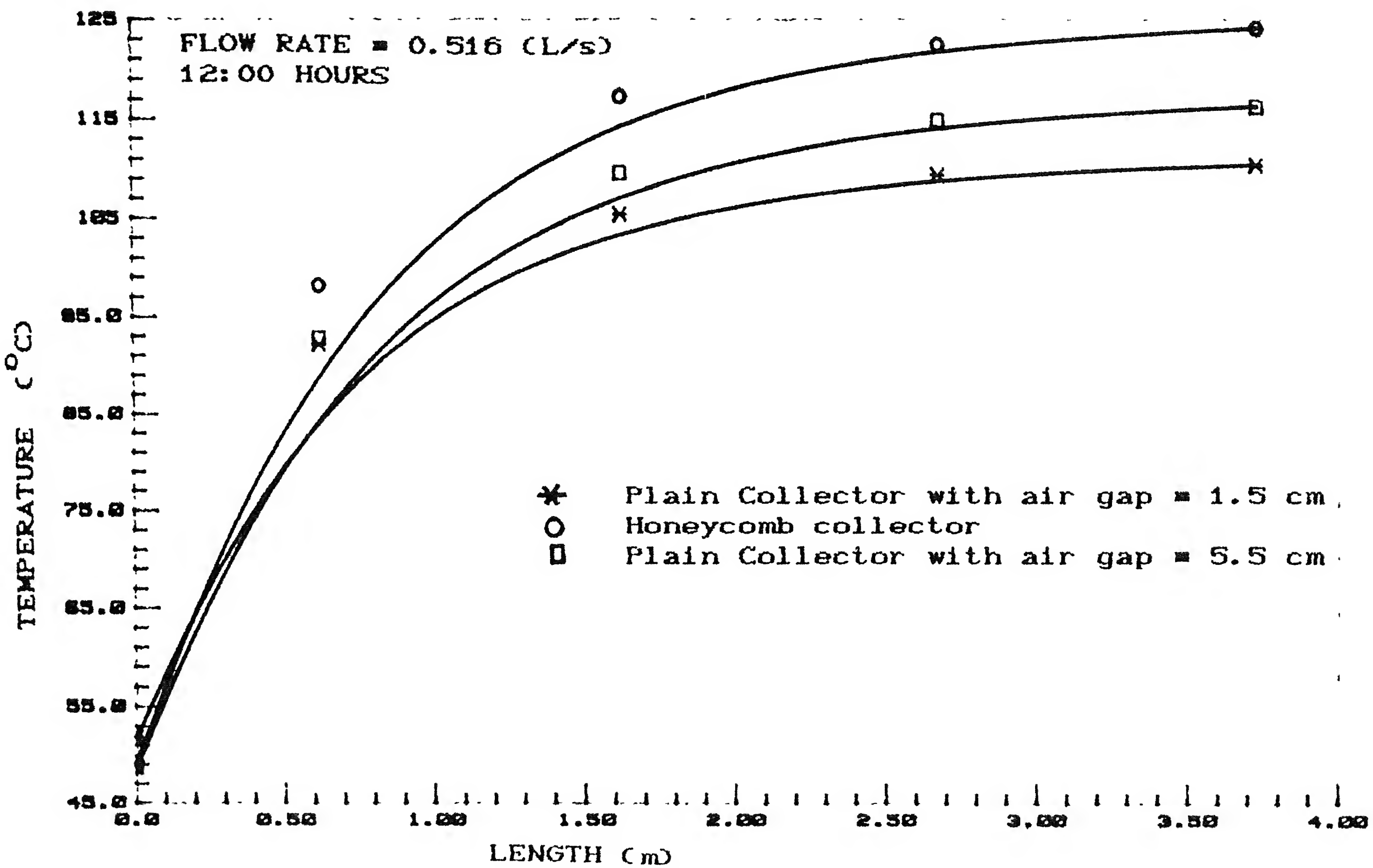


FIG. 5.14: VARIATION OF OUTLET AIR TEMPERATURE WITH COLLECTOR LENGTH.

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initial portions of the collector. Therefore, it is not advisable to increase the collector length indefinitely to obtain greater collector temperatures.

## 5.2 CONCLUSIONS

The experimental investigation of a solar air heater with honeycomb transparent insulation leads to the following conclusions:

1. For the same flow rate and the same cover glass area, a honeycomb collector yields much higher temperatures as compared to those for a simple flat plate collector.

2. The collector efficiency of a honeycomb collector is greater than that of a simple flat plate collector for the same flow rate.

3. The outlet air temperature and the collector efficiency can be increased significantly by increasing the absorber plate-glass cover air gap in a simple flat plate collector.

4. The collector efficiency increases with the flow rate for both the honeycomb and the plain collectors, in the range of the flow rates used in the experiment.

5. The rate of increase of air temperature falls rapidly with the collector length.

## 5.3 SUGGESTIONS FOR FUTURE WORK

The present study deals with the effect of a perspex honeycomb on the suppression of the frontal heat losses of a flat plate air heater. Primarily, it is the losses due to natural convection in the absorber-glass cover air gap which are suppressed. With the hydraulic diameter ($d_h$) of the honeycomb cell chosen equal to 2.0 cm, it does not have much effect on the suppression of the longwave radiation losses of the collector (Sec. 2.8). Therefore, work needs to be done on a honeycomb with cells of hydraulic diameter of approximately 0.5 cm, so that both the convective and the radiative losses can be suppressed. Alternatively, radiation suppression can be done by providing a low emissivity surface at one of the insulation's bounding faces, or by using a selective coating on the absorber.

Work also needs to be done on other honeycomb materials, which are inexpensive and have better optical transmission properties and radiation absorptivity in the far infrared region, as compared to perspex. It is also necessary to develop honeycomb materials with higher melting points since perspex shows deformation at temperatures exceeding 110 $^{o}$C. Temperature resistant glass capillaries offer exciting research possibilities in this regard.

Besides plastic honeycombs,aerogels also offer possibilities in the field of transparent insulation and these should be investigated.

It is also worth studying whether the multiple glazing can serve replacement of costly and complex honeycomb structures in the suppression of convective and radiative heat losses from the absorber plate.

Finally, work also needs to be done on a storage system to be used in conjunction with the honeycomb collector, so as to make it an integrated air heating system.

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# APPENDIX - A

## COLLECTOR EFFICIENCY

The collector efficiency is given by the relation:

$$\eta = \frac{\rho\ Q\ C_p}{A_c\ H_t\ R}\ [\ \int (\ T_{f,e} - T_{f,i}\ )\ dt] \qquad (1)$$

Where,

$\rho$, is the density of air flowing through the channels

Q, is the volume flow rate

$C_p$, is the specific heat of air,

$T_{fi}$, is the inlet air temperature

$T_{fe}$, is the outlet temperature

dt, is the time interval for each reading.

$A_c$, is the cover glass area

$H_t$, is the incident solar radiation on a horizontal surface

R , is the correction factor to account for the tilt of the collector from the horizontal.

Simpson's rule for calculating the area under a curve is

$$\int f(x)dx = \frac{t}{3}\ [\ y_\theta + 4y_1 + 2y_2 + 4y_3 + \dots 4y_{n-1} + y_n] \qquad (2)$$

for even n.

Where, $(x_\theta, y_\theta)$, $(x_1, y_1)$, $(x_2, y_2)$, ....... $(x_n, y_n)$ are n+1 data points. The temperature readings were taken after every two hours, therefore, dt is equal to two hours.

Using Equation (1) & (2), the collector efficiency is calculated for each of the flow rates used, with the collector in different configurations.

We now calculate the efficiency for the honeycomb collector with flow rate of 1.632 L/s.

The mean air temperature is $\frac{31.8 + 115.7}{2} = 73.8\ ^{o}C$. At this temperature ,the thermodynamic properties of air are:

$\rho \quad = \quad 1.008\ kg/m^3$

$C_p \quad = \quad 1.009\ kJ/kg.K$

The value of incident solar radiation for the month of May for Jodhpur is used for calculations. This value, modified for the tilt of the collector from the horizontal, is 7.41 kW-hr/sq.m., (correction factor R = 0.97).

A table giving the value of temperature rise for the flow rate of 1.632 L/s for the honeycomb collector is given below:

| HOUR OF THE DAY | TEMPERATURE RISE $^{o}C$ |
|---|---|
| 6.00 | 1.2 |
| 8.00 | 20.4 |
| 10.00 | 49.1 |
| 12.00 | 64.0 |
| 14.00 | 55.5 |
| 16.00 | 26.2 |
| 18.00 | 2.1 |

Using the values of temperature and the thermodynamic variables given above, the efficiency, $\eta$, comes out to be equal to:

$$\eta = 12.4 \%$$

The efficiency for other flow rates can be obtained similarly.

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